

PATENT COOPERATION TREATY

PCT

From the INTERNATIONAL BUREAU

NOTIFICATION OF THE RECORDING
OF A CHANGE(PCT Rule 92bis.1 and
Administrative Instructions, Section 422)

To:

GRANLEESE, Rhian, Jane
Marks & Clerk
57-60 Lincoln's Inn Fields
London WC2A 3LS
ROYAUME-UNI

Date of mailing (day/month/year) 11 December 2001 (11.12.01)		IMPORTANT NOTIFICATION International filing date (day/month/year) 27 September 2000 (27.09.00)	
Applicant's or agent's file reference WPP81111			
International application No. PCT/GB00/03709			
1. The following indications appeared on record concerning: <input checked="" type="checkbox"/> the applicant <input type="checkbox"/> the inventor <input type="checkbox"/> the agent <input type="checkbox"/> the common representative			
Name and Address TERAPROBE LIMITED Five Chancery Lane London EC4A 1BU United Kingdom		State of Nationality GB	State of Residence GB
		Telephone No.	
		Facsimile No.	
		Teleprinter No.	
2. The International Bureau hereby notifies the applicant that the following change has been recorded concerning: <input checked="" type="checkbox"/> the person <input type="checkbox"/> the name <input type="checkbox"/> the address <input type="checkbox"/> the nationality <input type="checkbox"/> the residence			
Name and Address TERAVIEW LIMITED 302/304 Cambridge Science Park Milton Road Cambridge CB4 0WG United Kingdom		State of Nationality GB	State of Residence GB
		Telephone No.	
		Facsimile No.	
		Teleprinter No.	
3. Further observations, if necessary:			
4. A copy of this notification has been sent to: <input checked="" type="checkbox"/> the receiving Office <input type="checkbox"/> the designated Offices concerned <input type="checkbox"/> the International Searching Authority <input checked="" type="checkbox"/> the elected Offices concerned <input checked="" type="checkbox"/> the International Preliminary Examining Authority <input type="checkbox"/> other:			
The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No.: (41-22) 740.14.35		Authorized officer Anman QIU Telephone No.: (41-22) 338.83.38	

PATENT COOPERATION TREATY

PCT

NOTIFICATION OF THE RECORDING
OF A CHANGE(PCT Rule 92bis.1 and
Administrative Instructions, Section 422)

From the INTERNATIONAL BUREAU

To:

GRANLEESE, Rhian, Jane
Marks & Clerk
57-60 Lincoln's Inn Fields
London WC2A 3LS
ROYAUME-UNI

Date of mailing (day/month/year) 06 juillet 2001 (06.07.01)	IMPORTANT NOTIFICATION
Applicant's or agent's file reference WPP81111	
International application No. PCT/GB00/03709	International filing date (day/month/year) 27 septembre 2000 (27.09.00)

1. The following indications appeared on record concerning:		
<input checked="" type="checkbox"/> the applicant	<input type="checkbox"/> the inventor	<input type="checkbox"/> the agent <input type="checkbox"/> the common representative
Name and Address TOSHIBA RESEARCH EUROPE LIMITED 260 Cambridge Science Park Milton Road Cambridge Cambridgeshire CB4 0WE United Kingdom	State of Nationality GB	State of Residence GB
	Telephone No.	
	Facsimile No.	
	Teleprinter No.	
2. The International Bureau hereby notifies the applicant that the following change has been recorded concerning:		
<input checked="" type="checkbox"/> the person	<input checked="" type="checkbox"/> the name	<input checked="" type="checkbox"/> the address <input type="checkbox"/> the nationality <input type="checkbox"/> the residence
Name and Address TERAPROBE LIMITED Five Chancery Lane London EC4A 1BU United Kingdom	State of Nationality GB	State of Residence GB
	Telephone No.	
	Facsimile No.	
	Teleprinter No.	
3. Further observations, if necessary:		
4. A copy of this notification has been sent to:		
<input checked="" type="checkbox"/> the receiving Office	<input type="checkbox"/> the designated Offices concerned	
<input type="checkbox"/> the International Searching Authority	<input checked="" type="checkbox"/> the elected Offices concerned	
<input checked="" type="checkbox"/> the International Preliminary Examining Authority	<input type="checkbox"/> other:	

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer Dominique DELMAS
Facsimile No.: (41-22) 740.14.35	Telephone No.: (41-22) 338.83.38

PATENT COOPERATION TREATY

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NOTIFICATION OF ELECTION

(PCT Rule 61.2)

From the INTERNATIONAL BUREAU

To:

Commissioner
 US Department of Commerce
 United States Patent and Trademark
 Office, PCT
 2011 South Clark Place Room
 CP2/5C24
 Arlington, VA 22202
 ETATS-UNIS D'AMERIQUE
 in its capacity as elected Office

Date of mailing (day/month/year) 28 May 2001 (28.05.01)	
International application No. PCT/GB00/03709	Applicant's or agent's file reference WPP81111
International filing date (day/month/year) 27 September 2000 (27.09.00)	Priority date (day/month/year) 27 September 1999 (27.09.99)
Applicant ARNONE, Donald, Dominic et al	

1. The designated Office is hereby notified of its election made:

☒ in the demand filed with the International Preliminary Examining Authority on:

26 April 2001 (26.04.01)

☐ in a notice effecting later election filed with the International Bureau on:2. The election ☒ was☐ was not

made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No.: (41-22) 740.14.35	Authorized officer Olivia TEFY Telephone No.: (41-22) 338.83.38
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(19) World Intellectual Property Organization
International Bureau(43) International Publication Date
5 April 2001 (05.04.2001)

PCT

(10) International Publication Number
WO 01/23956 A3(51) International Patent Classification⁷: **G02F 1/35,**
H03D 9/00, H01Q 9/00(21) International Application Number: **PCT/GB00/03709**(22) International Filing Date:
27 September 2000 (27.09.2000)

(25) Filing Language: English

(26) Publication Language: English

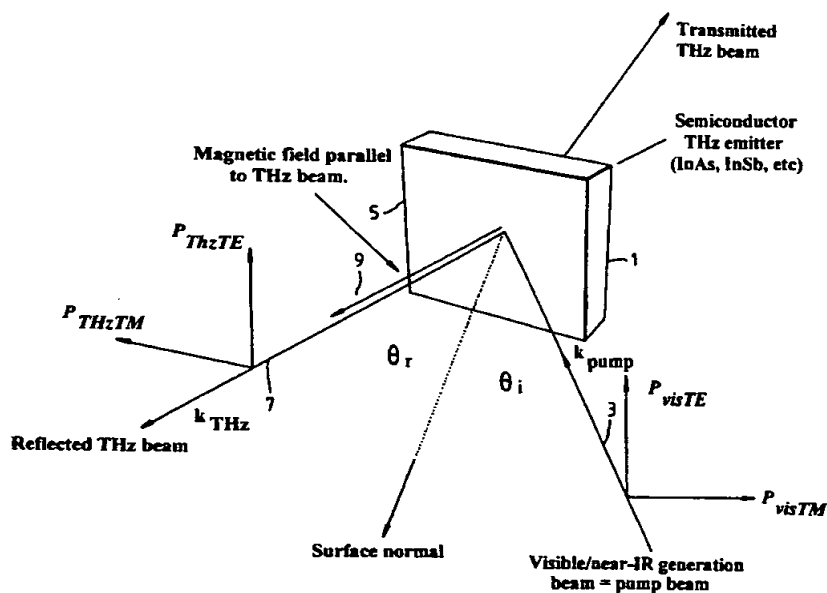
(30) Priority Data:
9922859.5 27 September 1999 (27.09.1999) GB(71) Applicant (for all designated States except US): **TER-
APROBE LIMITED** [GB/GB]; Five Chancery Lane, Lon-
don EC4A 1BU (GB).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **ARNONE, Donald,**
Dominic [US/GB]; c/o Toshiba Research Europe Limited,
Cambridge Research Laboratory, 260 Cambridge Science
Park, Milton Road, Cambridge CB4 0WE (GB). **CIESLA,**Craig, Michael [GB/GB]; c/o Toshiba Research Europe
Limited, Cambridge Research Laboratory, 260 Cambridge
Science Park, Milton Road, Cambridge CB4 0WE (GB).(74) Agent: **GRANLEESE, Rhian, Jane;** Marks & Clerk,
57-60 Lincoln's Inn Fields, London WC2A 3LS (GB).(81) Designated States (national): AE, AG, AL, AM, AT, AU,
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ,
DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR,
HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR,
LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ,
NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM,
TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.(84) Designated States (regional): ARIPO patent (GH, GM,
KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian
patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European
patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE,
IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG,
CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).Published:
— with international search report

[Continued on next page]

(54) Title: A RADIATION SOURCE



(57) Abstract: A radiation source comprising a frequency conversion member (1) configured to emit a beam of emitted radiation (7) with at least one frequency in the range from 0.1 THz to 100 THz, in response to irradiation with an input beam (3) with a frequency different to that of the emitted radiation (7), the source being subjected to a magnetic field (9) which has a component parallel to that of the emitted beam of radiation (7). The radiation source may be optimised by using both the fluence of the input beam and the magnetic field or may comprise a magnetically doped frequency conversion member or also have means for applying an electric field.

WO 01/23956 A3



(88) Date of publication of the international search report:
11 October 2001

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.



Published:

— *Without international search report and to be republished upon receipt of that report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

PATENT COOPERATION TREATY

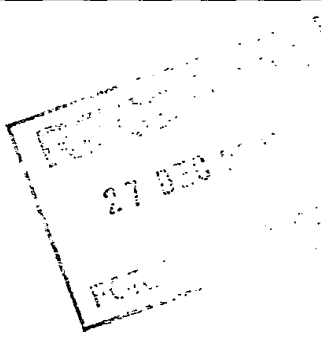
From the
INTERNATIONAL PRELIMINARY EXAMINING AUTHORITY

improvement

PCT

To:

GRANLEESE, Rhian Jane
MARKS & CLERK
57-60 Lincoln's Inn Fields
London WC2A 3LS
GRANDE BRETAGNE



NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Rule 71.1)

Date of mailing
(day/month/year) 14.12.2001

Applicant's or agent's file reference
WPP81111

IMPORTANT NOTIFICATION

International application No.
PCT/GB00/03709

International filing date (day/month/year)
27/09/2000

Priority date (day/month/year)
27/09/1999

Applicant
TERAPROBE LIMITED et al.

1. The applicant is hereby notified that this International Preliminary Examining Authority transmits herewith the international preliminary examination report and its annexes, if any, established on the international application.
2. A copy of the report and its annexes, if any, is being transmitted to the International Bureau for communication to all the elected Offices.
3. Where required by any of the elected Offices, the International Bureau will prepare an English translation of the report (but not of any annexes) and will transmit such translation to those Offices.

4. REMINDER

The applicant must enter the national phase before each elected Office by performing certain acts (filing translations and paying national fees) within 30 months from the priority date (or later in some Offices) (Article 39(1)) (see also the reminder sent by the International Bureau with Form PCT/IB/301).

Where a translation of the international application must be furnished to an elected Office, that translation must contain a translation of any annexes to the international preliminary examination report. It is the applicant's responsibility to prepare and furnish such translation directly to each elected Office concerned.

For further details on the applicable time limits and requirements of the elected Offices, see Volume II of the PCT Applicant's Guide.

Name and mailing address of the IPEA/

 European Patent Office
D-80298 Munich
Tel. +49 89 2399 - 0 Tx: 523656 epmu d
Fax: +49 89 2399 - 4465

Authorized officer

De Caemel, J-M

Tel. +49 89 2399-2251



PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference WPP81111	FOR FURTHER ACTION See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)	
International application No. PCT/GB00/03709	International filing date (day/month/year) 27/09/2000	Priority date (day/month/year) 27/09/1999
International Patent Classification (IPC) or national classification and IPC G02F1/35		
Applicant TERAPROBE LIMITED et al.		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.



2. This REPORT consists of a total of 7 sheets, including this cover sheet.

- ☐ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

These annexes consist of a total of sheets.

3. This report contains indications relating to the following items:

- I ☒ Basis of the report
- II ☐ Priority
- III ☒ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- IV ☐ Lack of unity of invention
- V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- VI ☐ Certain documents cited
- VII ☒ Certain defects in the international application
- VIII ☒ Certain observations on the international application

Date of submission of the demand 26/04/2001	Date of completion of this report 14.12.2001
Name and mailing address of the international preliminary examining authority:  European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Kiernan, L Telephone No. +49 89 2399 2185 

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/GB00/03709

I. Basis of the report

1. With regard to the **elements** of the international application (*Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report since they do not contain amendments (Rules 70.16 and 70.17)*):

Description, pages:

1-31 as originally filed

Claims, No.:

1-25 as originally filed

Drawings, sheets:

1/21-21/21 as originally filed

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.

These elements were available or furnished to this Authority in the following language: , which is:

- ☐ the language of a translation furnished for the purposes of the international search (under Rule 23.1(b)).
- ☐ the language of publication of the international application (under Rule 48.3(b)).
- ☐ the language of a translation furnished for the purposes of international preliminary examination (under Rule 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

- ☐ contained in the international application in written form.
- ☐ filed together with the international application in computer readable form.
- ☐ furnished subsequently to this Authority in written form.
- ☐ furnished subsequently to this Authority in computer readable form.
- ☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
- ☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.

4. The amendments have resulted in the cancellation of:

- ☐ the description, pages:
- ☐ the claims, Nos.:

**INTERNATIONAL PRELIMINARY
EXAMINATION REPORT**

International application No. PCT/GB00/03709

☐ the drawings, sheets:

5. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

(Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.)

6. Additional observations, if necessary:

III. Non-establishment of opinion with regard to novelty, inventive step and industrial applicability

1. The questions whether the claimed invention appears to be novel, to involve an inventive step (to be non-obvious), or to be industrially applicable have not been examined in respect of:

☐ the entire international application.

☒ claims Nos. 1-11, 21-25.

because:

☐ the said international application, or the said claims Nos. relate to the following subject matter which does not require an international preliminary examination (*specify*):

☒ the description, claims or drawings (*indicate particular elements below*) or said claims Nos. 1,2,10,11,21-25 are so unclear that no meaningful opinion could be formed (*specify*):
see separate sheet

☐ the claims, or said claims Nos. are so inadequately supported by the description that no meaningful opinion could be formed.

☒ no international search report has been established for the said claims Nos. 3-9.

2. A meaningful international preliminary examination cannot be carried out due to the failure of the nucleotide and/or amino acid sequence listing to comply with the standard provided for in Annex C of the Administrative Instructions:

☐ the written form has not been furnished or does not comply with the standard.

☐ the computer readable form has not been furnished or does not comply with the standard.

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N) Yes: Claims 13,14

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/GB00/03709

	No:	Claims	12,15,16,18-20
Inventive step (IS)	Yes:	Claims	13,14
	No:	Claims	
Industrial applicability (IA)	Yes:	Claims	1-25
	No:	Claims	

2. Citations and explanations
see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:
see separate sheet

VIII. Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:
see separate sheet

The following documents are considered in this International Preliminary Examination Report:

D1: SARUKURA N ET AL: 'High average-power THz radiation from femtosecond laser-irradiated InAs in a magnetic field and its elliptical polarization characteristics' JOURNAL OF APPLIED PHYSICS, 1 JULY 1998, AIP, USA, vol. 84, no. 1, pages 654-656, ISSN: 0021-8979 cited in the application.

SECTION III

1. No opinion with regard to novelty, inventive step and industrial applicability could be established concerning claims 1-11 for the following reasons:
 - 1.1 The subject-matter of claims 3-8 (also claims 9-11 while being dependent on claims 3-8) has not been searched by the ISA (see corresponding search report).
 - 1.2 The subject-matter of independent claims 1, 2, and 21-25 is so unclear (see Section VIII, 1.1-1.3) that no meaningful examination is possible.

SECTION V

1. Independent device claim 12 defines the various structural elements of a radiation source. In this regard, document D1 discloses a radiation source, which generates THz radiation from laser-irradiated InAs in a magnetic field (see for example Fig. 1 and associated text). The InAs sample in D1 was placed at 45° to the input laser beam and the emitted THz beam was produced by reflecting the input beam off a surface of the InAs sample (or frequency conversion member in the parlance of the application). Further, it is disclosed in D1 that depending on the magnitude of the applied magnetic field a variation in polarization of the emitted THz beam can be induced (see Fig. 5(a, b and c) and associated text). Therefore, the magnetic field will have "a component" parallel to that of the emitted beam. Consequently,

the subject-matter of claim 12 (also claims 15, 16, 18-20) is not novel, within the meaning of Article 33(1) PCT, with respect to the disclosure of document D1.

2. None of the prior art documents, available at this present time, suggest or anticipate that the magnetic field should be oriented parallel to the direction of the emitted Thz beam. Thus, it appears that the subject-matter of claim 13 (also claim 14, incorporated in claim 12) would satisfy the requirements of Article 33(3) PCT.

SECTION VII

1. The independent claims are not in the two-part form in accordance with Rule 6.3(b) PCT, which in the present case would be appropriate, with those features known in combination from the prior art document D1 being placed in the preamble (Rule 6.3(b)(i) PCT) and with the remaining features being included in the characterising part (Rule 6.3(b)(ii) PCT).
2. The features of the claims are not provided with reference signs placed in parentheses (Rule 6.2(b) PCT).

SECTION VIII

1. The wording of the claims is not sufficiently clear, under Article 6 PCT, for the following reasons:
 - 1.1 The subject-matter of independent device claim 1 concerns the definition of the structural device features of a radiation source. Claim 1 defines that the free carrier concentration of the frequency conversion member and the applied magnetic field is configured such that "the cyclotron diameter of the free carriers of the frequency conversion member is within 30% of their scattering length". This formulation does not establish a definition of **permanent device features** which could be used to compare the subject-matter of the claim with the prior art. Claim 2 defines that free carrier concentration of the frequency conversion member and the applied magnetic field is configured to minimise "the screening effect of free carriers in the

frequency conversion member". Again, this formulation does not establish a definition of **permanent device features** which could be used to compare the subject-matter of the claim with the prior art. The formulations mentioned above, would more appropriately define method steps required to optimise a radiation source, also resulting in some confusion as to the category of claims 1 and 2.

- 1.2 Independent method claims 21 and 22 attempt to define a method of optimising a radiation source wherein either the strength of the applied magnetic field, or the laser fluence, respectively, is selected in order to "minimise the screening of the surface field of the frequency conversion member". These formulations amount to an attempt by the Applicant to claim the underlying technical problem in the field of ultra short Thz pulse generation, without clearly expressing those method steps necessary to carry out the optimisation process. As pointed out in D1, for example, the THz-radiation power (see Fig. 2 for example) does not increase linearly with incident excitation power. For a given value of applied magnetic field (in this case 1.7 T) the output of the Thz source saturates at high laser excitation powers, which is essentially (albeit at a lower magnetic field strength) the same as that shown in figure 18 of the present application. As far as can be understood the required method steps for optimisation of the Thz source appear to be adequately defined by claim 23.
- 1.3 Claims 24 and 25 contain references to the description and the drawings. According to Rule 6.2(a) PCT, claims should not contain such references except where absolutely necessary, which is not the case here.

A. CLASSIFICATION OF SUBJECT MATTER IPC 7 G02F1/35 H01Q 00 H01Q9/00		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) IPC 7 G02F H03D H01Q		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practical, search terms used) INSPEC, EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	IZUMIDA S ET AL: "SPECTRUM CONTROL OF THZ RADIATION FROM INAS IN A MAGNETIC FIELD BY DURATION AND FREQUENCY CHIRP OF THE EXCITATION PULSES" APPLIED PHYSICS LETTERS, US, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, vol. 75, no. 4, 26 July 1999 (1999-07-26), pages 451-453, XP000860652 ISSN: 0003-6951	21,22
A	the whole document <div style="text-align: center;">--- -/--</div>	1,2,11, 15,18,19
<input checked="" type="checkbox"/> Further documents are listed in the continuation of box C. <input type="checkbox"/> Patent family members are listed in annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 18 December 2000		Date of mailing of the international search report 08.03.01
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016		Authorized officer DIOT, P

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>GU P ET AL: "Magnetic field dependence of THz radiation from InSb surface"</p> <p>TECHNICAL DIGEST. SUMMARIES OF PAPERS PRESENTED AT THE CONFERENCE ON LASERS AND ELECTRO-OPTICS. POSTCONFERENCE EDITION. CLEO '99. CONFERENCE ON LASERS AND ELECTRO-OPTICS (IEEE CAT. NO.99CH37013), TECHNICAL DIGEST. SUMMARIES OF PAPERS PRESENTED AT THE,</p> <p>pages 372-373, XP002155597</p> <p>1999, Washington, DC, USA, Opt. Soc. America, USA</p> <p>ISBN: 1-55752-595-1</p> <p>the whole document</p> <p>---</p>	1,2, 21-23
X	<p>SARUKURA N ET AL: "High average-power THz radiation from femtosecond laser-irradiated InAs in a magnetic field and its elliptical polarization characteristics"</p> <p>JOURNAL OF APPLIED PHYSICS, 1 JULY 1998, AIP, USA,</p> <p>vol. 84, no. 1, pages 654-656,</p> <p>XP002155598</p> <p>ISSN: 0021-8979</p> <p>cited in the application</p> <p>the whole document</p> <p>---</p>	21,22
A		12
A	<p>BENICEWICZ P K ET AL: "Scaling of terahertz radiation from large-aperture biased InP photoconductors"</p> <p>OPTICS LETTERS, 15 AUG. 1993, USA,</p> <p>vol. 18, no. 16, pages 1332-1334,</p> <p>XP000384364</p> <p>ISSN: 0146-9592</p> <p>the whole document</p> <p>---</p>	21-23
A	<p>ZHANG X C: "MAGNETIC SWITCHING OF THZ BEAMS"</p> <p>APPLIED PHYSICS LETTERS, US, AMERICAN INSTITUTE OF PHYSICS. NEW YORK,</p> <p>vol. 62, no. 17,</p> <p>26 April 1993 (1993-04-26), pages</p> <p>2003-2005, XP000364770</p> <p>ISSN: 0003-6951</p> <p>cited in the application</p> <p>the whole document</p> <p>-----</p>	1

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB 00/03709

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This international Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

See PCT/ISA/210 (Extra Sheet)

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority and multiple (groups of) inventions in this international application, as follows:

1. Claims: 1,2, 9-11 (as far as depending on claims 1 or 2),
13-20 (as far as depending on claims 1, or 2),
21-25

Independent claims 1, 2, 21, 22 relate to a radiation source comprising a frequency conversion member configured to emit a beam of radiation in response to an input beam at a frequency different to that of the input, the frequency conversion member being subjected to a magnetic field. It appears that these four independent claims relate to the optimisation of the source, i.e. it is possible to predict an optimum optical fluence for a given magnetic field.

- 1.1. Claims: 12, 13-19 (as far as depending on claim 12).

A radiation source comprising a frequency conversion member configured to emit a beam of radiation in response to an input beam at a frequency different to that of the input, the frequency conversion member being subjected to a magnetic field which has a component parallel to that of the emitted beam of radiation, the emitted beam of radiation being produced by reflecting the input beam off a surface of said frequency conversion member.

2. Claims: 3,4

A radiation source comprising a frequency conversion member configured to emit a beam of radiation in response to an input beam at a frequency different to that of the input, the frequency conversion member comprises a magnetic material dopant.

3. Claims: 5-8, 9 (as far as depending on claim 5)

A radiation source comprising a frequency conversion member configured to emit a beam of radiation in response to an input beam at a frequency different to that of the input, the frequency conversion member being subjected to a magnetic field and the source comprises means for applying an electric field to the frequency conversion member.

Please note that all inventions mentioned under item 1, although not necessarily linked by a common inventive concept, could be searched

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(71) Applicant (for all designated States except US):
TOSHIBA RESEARCH EUROPE LIMITED [GB/GB];
260 Cambridge Science Park, Milton Road, Cambridge,
Cambridgeshire CB4 0WE (GB).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **ARNONE, Donald,**
Dominic [US/GB]; c/o Toshiba Research Europe Limited,

Cambridge Research Laboratory, 260 Cambridge Science
Park, Milton Road, Cambridge CB4 0WE (GB). **CIESLA,**
Craig, Michael [GB/GB]; c/o Toshiba Research Europe
Limited, Cambridge Research Laboratory, 260 Cambridge
Science Park, Milton Road, Cambridge CB4 0WE (GB).

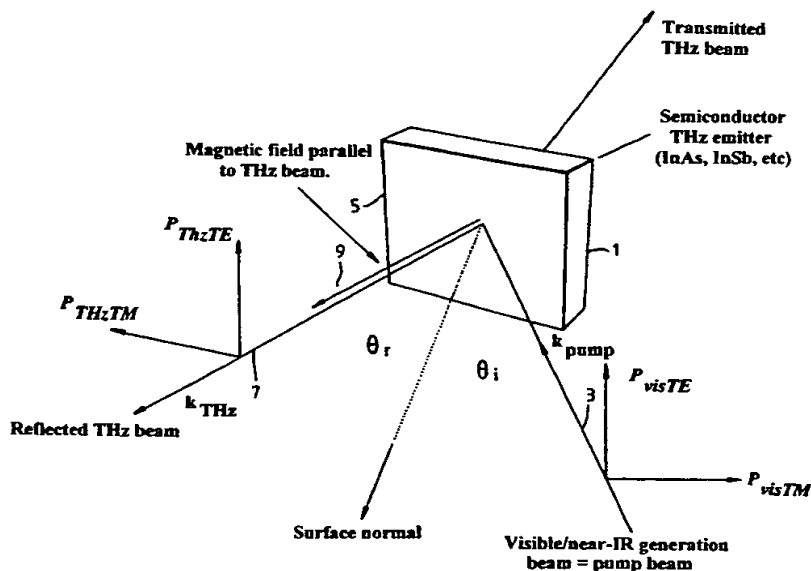
(74) Agent: **GRANLEESE, Rhian, Jane;** Marks & Clerk,
57-60 Lincoln's Inn Fields, London WC2A 3LS (GB).

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[Continued on next page]

(54) Title: A RADIATION SOURCE



(57) Abstract: A radiation source comprising a frequency conversion member (1) configured to emit a beam of emitted radiation (7) with at least one frequency in the range from 0.1 THz to 100 THz, in response to irradiation with an input beam (3) with a frequency different to that of the emitted radiation (7), the source being subjected to a magnetic field (9) which has a component parallel to that of the emitted beam of radiation (7). The radiation source may be optimised by using both the fluence of the input beam and the magnetic field or may comprise a magnetically doped frequency conversion member or also have means for applying an electric field.

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A Radiation Source

The present invention primarily relates to a radiation source for emitting radiation with frequencies ranging from the high Gigahertz range (GHz) up to and including the Terahertz range (THz). All such radiation is colloquially known as THz radiation, especially that in the range from 0.1 THz to 100 THz. More specifically, the present invention relates to a magnetically enhanced radiation source for such radiation.

Recently, there has been much interest in using THz radiation to look at a wide variety of samples using a range of methods. THz radiation has been used for both imaging samples and obtaining spectra. Recent work by Arnone et al, SPIE, European Conference Munich, June 1999, illustrates the use of THz radiation to image types of human and non human tissue.

THz radiation is of particular use because it penetrates most dry, non metallic and non polar objects like plastics, paper, cardboard and non polar organic substances. Therefore, THz radiation can be used instead of x-rays to look inside boxes, cases etc. THz has lower energy, non-ionising photons than X-rays, hence, the health risks of using THz radiation are expected to be vastly reduced compared to those using conventional X-rays.

To improve the usefulness of such THz radiation, there is a need to produce a THz source which can produce a relatively high energy beam of THz. To date, there are no compact solid state sources of THz radiation. However, recent advances in ultra fast pulsed lasers operating in the near infrared and visible have allowed coherent, broadband THz pulses to be produced from semiconductors. There are three widely-used methods for generating coherent THz from semiconductors irradiated by such ultrafast pulses : optical rectification, the surface field photocurrent effect, and lateral

photocurrent effect using antennas. THz radiation is produced by irradiating a semiconductor material which possesses suitable properties with an input beam of optical or infra-red radiation which can be produced by a standard laser such as a Ti:Sapphire Laser. It would seem logical that to produce a strong THz source, all that is required is a stronger input beam. However, this is not the case as the power of the emitted THz beam saturates as the power of the input beam is increased. Also, higher input beam powers may damage the crystal being irradiated.

It has been previously suggested that the THz output of such a semiconductor material can be controlled by subjecting the material to a magnetic field. Zhang et al. Appl. Phys. Lett. 62 2003 (1993) showed that the direction and polarisation of a THz beam produced from a non-linear semiconductor crystal (in this case GaAs) could be controlled by subjecting the non-linear material to a magnetic field. The magnetic field here was oriented perpendicular to both the input beam and the THz beam. The THz beam was produced by transmission of the input beam through the non-linear material.

Some et al. Phys. Rev. B 53, R13 295 (1996) also used transmission geometry to investigate how THz emission using transmission geometry was affected by an applied magnetic field. Here, the field was applied both perpendicular to the input beam (and hence perpendicular to the emitted beam) and also at an angle of 25° from the input beam.

Sarukura et al. Appl. Phys. Lett. 84, 654 (1998) have recently shown enhanced THz emission using reflection geometry. Here, the non-linear material was positioned at 45° to the input beam, such that the emitted (or more correctly, the reflected) beam and input beam are arranged at right angles. In this arrangement, the magnetic field was arranged parallel to the input beam, but perpendicular to the emitted beam. Using a magnetic field with a strength of 1.7T, Sarukura et al. achieved a THz beam having a power of several μ watts with a 1.5 W excitation power.

The present invention addresses the above problem of providing an enhanced source which is intended primarily for use on the THz frequency range and which has obtained better results than the previously discussed methods for enhancing THz emission.

In a first aspect, the present invention provides a radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam with a frequency different to that of the emitted radiation, the source being subjected to a magnetic field which has a component parallel to that of the emitted beam of radiation, the emitted beam of radiation being produced by reflecting the input beam off a surface of the frequency conversion member.

The source is primarily intended for use in the THz frequency range. Preferably, the emitted radiation has a frequency in range of 0.1 THz to 100THz, more preferably from 1THz to 84THz even more preferably, from 1 THz to 20 THz.

Reflection geometry is chosen as there are losses in the radiation power as the THz beam transverses the frequency conversion member in transmission geometry.

The radiation source of the present invention is capable of producing a more efficient THz beam. The source of Sarukura et al. is capable of a conversion efficiency of 4.3×10^{-5} . However, the present invention is capable of a conversion efficiency in excess of this figure. For example, the present invention has obtained conversion efficiencies of 4.3×10^{-3} .

Preferably, the magnetic field is arranged at an angle of 20° or less to the emitted or reflected beam. More preferably, the magnetic field is arranged completely parallel to the emitted or reflected beam.

A number of different frequency conversion member could be used for example LiIO_3 , $\text{NH}_4\text{H}_2\text{PO}_4$, ADP, KH_2AsO_4 , Quartz, AlPO_4 , ZnO, CdS, GaP, GaAs, BaTiO_3 , LiTaO_3 ,

LiNbO₃, Te, Se, ZnTe, ZnSe, Ba₂NaNb₅O₁₅, AgAsS₃, proustite, Cd, Se, CdSe, CdGeAs₂, AgGaSe₂, AgSbS₃, ZnS, BBO, KTP, DAST (4-N-methylstilbazolium), L₄NbO₃. The frequency conversion member will preferably be one of InAs, InSb or GaAs.

The magnetic field may be generated by an electro-magnet or a permanent magnet. The source may comprise such a magnet. Preferably the frequency conversion member is cooled.

Experiments using sources according to the above mentioned aspects of the present invention have shown that the conversion efficiency does not saturate with magnetic field for an appropriate choice of incident pump energy per unit area (optical fluence). Therefore, preferably, the frequency conversion member is subjected to a magnetic field of at least 2T.

How the efficiency of the emitted beam varies with the applied magnetic field is believed to be determined by at least three principal effects, the acceleration of surface charge due to the Lorentz force in a magnetic field; the carrier-carrier scattering of the free carriers of the frequency conversion member and the screening of the surface field of the frequency conversion member. Acceleration of charge due to Lorentz force in magnetic field, given by the formula:

$$E_{rad} \propto dJ / dt \propto dv / dt \propto E_{surf} + v \times B \quad (0)$$

where E_{rad} is the field of the radiation, J is the surface current, v is the velocity of charged force carriers and E_{surf} is the surface field.

Maximising the acceleration of charge will in general maximise the power of the emitted beam. The application of a magnetic field enhances the acceleration. However, the acceleration can be further enhanced by using a frequency conversion member which has been magnetically doped.

It has previously been shown that a large Faraday effect can be seen in semiconductors which have been doped using magnetic ions such as Mn.

In a second aspect, the present invention provides a radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to being irradiated with an input beam with a frequency different to that of the emitted beam, the frequency conversion member being doped with a magnetic material.

In use, the source is subjected to a magnetic field.

More preferably, the magnetic dopant is Mn. However, other magnetic dopants such as Tc or Re could be used.

The acceleration can also be enhanced by applying an electric field to the frequency conversion member in addition to the magnetic field.

Therefore, in a third aspect, the present invention provides a radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to being irradiated with an input beam with a frequency different to that of the emitted beam, the source being subjected to a magnetic field, the source further comprising means for applying an electric field at the surface of the frequency conversion member which is irradiated by the input beam.

The means for applying the electric field can be provided by two Ohmic contacts provided to the frequency conversion member and means for applying a bias to accelerate the photocarriers between these two contacts. The Ohmic contacts may be shaped so that they taper towards one another. In other words, they form a "bow-tie" shape.

The means may also be provided by a front gate which overlies the surface of the frequency conversion member which is irradiated by the input beam.

Preferably, the frequency conversion member comprises a magnetic dopant. More preferably, the magnetic dopant comprises Mn. Also, the input beam is preferably circularly polarised.

In the radiation sources of the second and third aspect of the present invention, the magnetic field preferably has a component parallel to that of the emitted beam. More preferably, the magnetic field is at an angle of at most 20° to the emitted beam.

More preferably, the emitted beam is produced by reflection of the input beam off a surface of the frequency conversion member.

Although it is always desirable to enhance the acceleration of the charge, scattering and screening also affect the efficiency of the source. The source can be viewed as having a low optical fluence regime and a high optical fluence regime. In the low fluence regime carrier-carrier scattering is the dominant mechanism limiting the enhancement of the power of the emitted beam. In the high fluence regime, screening of the surface electric field is the dominant mechanism which limits the enhancement of the power of the emitted beam.

In the presence of a fixed magnetic field such as one might find in a superconducting magnet in persistent mode (the type found for example in MRI machines) or a fixed permanent magnet, the two optical fluence regimes can be determined by plotting out the experimentally measured power of the emitted beam as function of adjusted optical fluence (determined by laser power and/or spot size adjustment, or other means) for different magnetic field values.

The time-averaged power of the emitted beam can be approximated with the expression:

$$P \propto \frac{n^2 B^2}{m^4} \left[\frac{\cos \theta_M \sin \theta_M}{2\theta_M} + \frac{1}{2} \right], \quad (1)$$

where P is the power of the emitted beam. n is the free carrier concentration. m is the effective mass of the carriers, B is the magnetic field. and θ_M represent the angle completed by the carrier at the time of the collision, and r is the cyclotron radius. This angle can be expressed as a function of the ratio $R = \lambda/r$ of the characteristic radius as

$$\theta_M = \arccos \left[1 - \frac{1}{2} \left(\frac{\lambda}{r} \right)^2 \right], \quad (2)$$

where λ is the mean free path which is defined as $n^{-1/3}/2$.

The above expression is only valid for $(\lambda/r) < \sqrt{2}$. For magnetic fields B smaller than 10T, (2) can be approximated as a linear function of B , $\theta_M \approx \alpha B$. In this limit, (1) reduces to:

$$P \propto \frac{1}{m^*} \left[\frac{B \sin(2\alpha B)}{4\alpha} + \frac{B^2}{2} \right] \quad (3)$$

Fitting the calculated emitted beam power of (1) as function of optical fluence (or equivalently, photogenerated carrier density n) with the measured values allows one to determine whether one is in the low or high optical fluence limit.

In the low fluence limit it is possible to fit (1) to the experimental data by applying a suitable multiplicative factor to one or the other data set. In the high fluence limit, there is significant deviation of experimental data below the prediction of (1) as the optical fluence increases.

In this high fluence regime, it is believed that screening dominates and reduces the source efficiency, i.e. the (emitted beam power)/(the input beam power) as the optical fluence increases. In the high optical fluence regime, screening of the surface field becomes the dominant mechanism, and the term E_{surf} is dramatically reduced.

It is often desirable to generate the largest power possible from a source. Increasing the power of the input beam will in most (but not all) cases increase the power of the emitted beam. However, the screening which occurs in the high fluence regime means that once the high fluence regime is entered, the efficiency of the source decreases. Hence, it is not desirable to increase the input beam power to enter this regime. Therefore, there is a need to be able to determine the start of this regime. The inventors of the present invention have determined how to establish this and have also surprisingly found that the point at which this regime is entered is dependent upon the applied magnetic field as well as the fluence of the input beam.

Therefore, according to a fourth aspect, the present invention provides a radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam having a frequency different to that of the emitted beam of radiation, the source being subjected to a magnetic field, the magnetic field and fluence of the input beam being configured to minimise the screening effect of free carriers in the frequency conversion member.

In fifth aspect, the present invention provides a method of optimising a radiation source, the radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam with a frequency different to that of the emitted radiation,

the method comprising the step of applying a magnetic field to the source, the magnitude of the magnetic field being chosen in order to minimise the screening of the surface field of the frequency conversion member by free carriers in the frequency conversion member for a predetermined fluence of the input beam.

In a sixth aspect, the present invention provides a method of optimising a radiation source, the radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam with a frequency different to that of the emitted radiation,

the method comprising the step of applying a magnetic field to the source, the fluence of the input beam being chosen in order to minimise the screening of the surface field of the frequency conversion member by free carriers in the frequency conversion member for a predetermined magnitude of the applied magnetic field.

In the high optical fluence regime, the efficiency of the source can be optimised by determining the point at which the measured power deviates from the predicted value of (1) with increasing optical fluence for the applied magnetic field. It has been found that the point at which the emitted power deviates from that predicted by (1) varies exponentially with applied magnetic field. Therefore, by measuring the divergent values, it is possible to predict the optimum optical fluence for a given magnetic field and vice versa.

Therefore, preferably, the method of the fifth and sixth aspects of the present invention determine the magnitude of the magnetic field or the optical fluence by the steps of:

- a) measuring the power of the emitted beam as a function of optical fluence for at least three values of magnetic field;
- b) fitting the data measured in a) to the relation:

$$P \propto \frac{n^2 B^2}{m'} \left[\frac{\cos \theta_M \sin \theta_M}{2\theta_M} + \frac{1}{2} \right], \quad (1)$$

where P is the power of the emitted beam, n is the free carrier concentration, m is the effective mass of the carriers, B is the magnetic field and θ_M is :

$$\theta_M(n, B) = \arccos \left[1 - \frac{1}{2} \left(\frac{\lambda}{r} \right)^2 \right], \quad (2)$$

where λ is the mean free path which is defined as $1/2(n^{-1/3})$ and r is the cyclotron radius;

c) determining the fluence values for the at least three values of magnetic field where with increasing fluence, the measured power starts to diverge from the function of step b); and

d) fitting an exponential function to the at least three values determined in point c) such that the optimum fluence can be determined for a given magnetic field or an optimum magnetic field can be determined for a given fluence.

Preferably, the fitting in step (b) is performed by weighting the points with a lower optical fluence.

The exponential fit in step (d) is preferably made to the function having the general form:

$$F=F_0+A\exp(B/t)$$

where F is the fluence, B the magnetic field and F_0 , A and t are the parameters to be fitted. Once these parameters are determined, the optimum fluence for a given magnetic field or the optimum field for a given fluence can be determined.

The fluence values where the measured power starts to diverge can be taken as where the measured power drops more than 10% below the theoretical value, more preferably more than 5% below the theoretical value.

In the limit of low fluence, electron-electron scattering will reduce THz power appreciably until the limit where the cyclotron diameter (2r) is comparable to the electron-electron scattering length, i.e. 2r is close to the electron-electron scattering length $\lambda=n^{-1/3}/2$.

Therefore, in a seventh aspect, the present invention provides a radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation response to irradiation with an input beam with a frequency different to that of

the emitted radiation, the source being subjected to a magnetic field wherein the free carrier concentration of the frequency conversion member and the applied magnetic field is configured such that the cyclotron diameter of the free carriers in the frequency conversion member is within 30% of their scattering length.

The scattering length being defined by $\lambda = n^{-1/3}/2$. The cyclotron diameter can be 30% larger or 30% smaller than the scattering length.

Preferably, the cyclotron diameter of the free carriers is within 20% of the carrier-carrier scattering length, more preferably 10%, even more preferably 5%.

Both the cyclotron diameter and the electron-electron scattering length are dependent on B and n (optical fluence). Thus, these need to be optimised simultaneously.

Scattering between adjacent electrons results in decoherence of the waveforms of the emitted beam and hence reduce the emitted power. Decoherence here means that the emitted waveforms from the accelerated charge do not add or combine constructively, i.e. no constructive interference. In general, electron-electron (or more generally carrier-carrier) scattering is the dominant mechanism at lower optical fluences, leading to low photogenerated carrier densities. The above ensures that the length of the electron trajectory s is maximised before scattering off the next adjacent electron located λ away.

Typically, the wavelength of the input or pump beam for any of the above sources will be such that the photon pump energy is larger than the band gap of the frequency conversion member. Preferably, source will be configured such that the input beam is at the Brewster angle of the frequency conversion member, i.e. at the Brewster angle to the surface normal. The Brewster angle will be about 70° to the surface normal. Therefore, typically, the input beam will be preferably arranged between 45° and 85°, more preferably between 60° and 80°.

It should be noted that a radiation source may be provided which comprises any combination of a magnetically doped frequency conversion member and means for applying an electric field to the frequency conversion member. This source may also be configured with the reflection geometry of the first aspect of the present invention. The applied magnetic field and the fluence of the input beam may also be optimised to reduce scattering or screening effects in a source having a magnetically doped frequency conversion member and/or means for applying an electric field to the frequency conversion member and/or which is configured with the reflection geometry of the first aspect of the present invention.

All of the above sources are preferably used to generate radiation having at least one frequency in the range from 0.1 THz to 100 THz. The input beam may be a pulsed beam or a so-called CW beam.

The present invention will now be described with reference to the following preferable, non-limiting embodiments, in which:

Figure 1 is a schematic of a source in accordance with an embodiment of the present invention;

Figure 2 is a schematic of the experimental arrangement to measure a source according to an embodiment of the present invention;

Figures 3a and 3b are plots of the transverse magnetic and transverse electric polarisation direction of a THz electric field emitted by a source according to an embodiment of the present invention;

Figure 4 shows a plot of the transverse magnetic polarisation component of a THz emission spectra from a source according to an embodiment of the present invention;

Figures 5a and 5b show plots of the power calculated from the transverse magnetic and the transverse electric polarisations respectively, figure 5c plots the total power;

Figure 6 is a plot of THz power from an InAs source according to an embodiment of the present invention;

Figure 7 shows a plot of THz conversion efficiency and THz pulse energy against the energy of the visible pulse;

Figure 8 is a plot comparing the efficiency of THz generation according to an embodiment of the present invention as compared with the known prior art;

Figure 9 shows a compact THz emitter in accordance with an embodiment of the present invention;

Figure 10 shows a compact THz emitter in accordance with a further embodiment of the present invention;

Figure 11 shows a compact emitter in accordance with another embodiment of the present invention;

Figure 12 shows a THz emitter in accordance with another embodiment of the present invention;

Figure 13 shows a variation on the emitter of Figure 12;

Figure 14 shows a magnetically doped THz emitter in accordance with an embodiment of the present invention;

Figure 15 shows an experimental arrangement for detecting THz radiation from the source of Figure 14;

Figure 16 shows an embodiment of the present invention which uses an electric field as well as a magnetic field to enhance THz production;

Figure radiation with at least one frequency in the range from 0.1 THz to 100 THz 17 shows a further embodiment of the present invention where a front gate overlies a surface of the THz emitter;

Figure 18 shows a plot of the power of the emitted beam against the optical fluence of the input beam for a source in accordance with an embodiment of the present invention;

Figure 19 shows a schematic cyclotron orbit of a carrier in the frequency conversion member of a source in accordance with an embodiment of the present invention;

Figure 20 shows a plot of the cyclotron orbit radius against the optical fluence of the input beam of a source in accordance with an embodiment of the present invention;

Figure 21 shows a plot of the power of the emitted THz beam against the applied magnetic field of a source in accordance with an embodiment of the present invention;

Figure 22 shows a Monte Carlo simulation of the electric field against depth from the surface of a source in accordance with an embodiment of the present invention; and

Figure 23 shows a plot of optical fluence of the input beam against the applied magnetic field for a source in accordance with an embodiment of the present invention, the solid line shows the optimal magnetic field for a set fluence.

Figure 1 shows a THz emitter according to an embodiment of the present invention. The THz emitter has a frequency conversion member 1 which is either InAs, InSb, or GaAs.

It should be noted that other types of frequency conversion member are possible either crystalline or non-crystalline. For example, LiIO_3 , $\text{NH}_4\text{H}_2\text{PO}_4$, ADP, KH_2AsO_4 , Quartz, AlPO_4 , ZnO , CdS , GaP , GaAs , BaTiO_3 , LiTaO_3 , LiNbO_3 , Te , Se , ZnTe , ZnSe , $\text{Ba}_2\text{NaNb}_5\text{O}_{15}$, AgAsS_3 , proustite, Cd , Se , CdSe , CdGeAs_2 , AgGaSe_2 , AgSbS_3 , ZnS , BBO , KTP , DAST (4-N-methylstilbazolium), LiNbO_3 .

A pump beam 3 is directed towards member 1 at an angle θ_i to the surface normal of member 1. The pump beam is reflected from the surface 5 of emitter 1 as a THz beam at an angle θ_r to the surface 5 normal. The emitter is subject to a magnetic field along the direction of the emitted THz beam 7. As the magnetic field direction 9 is parallel to the direction of the THz beam 7, both the transverse electric $P_{\text{THz}}T_E$ and the transverse magnetic $P_{\text{THz}}T_M$ polarisation components of the THz beam are subject to a magnetic field.

The pump beam will typically have wavelengths in the range 2mm to 350nm. The pump wavelength will be such that the pump photon energy is larger than the band gap energy of the frequency conversion member 1. The pump beam will be a pulsed beam with a plurality of frequencies contained within each pulse. The semiconductor frequency conversion member 1 can emit a THz beam that is a difference of two of the frequencies in the pump beam.

Figure 2 shows an experimental arrangement which is used to generate THz in accordance with an embodiment of the present invention. A mode-locked Ti:Sapphire Laser 21 produces a beam 23 of 90 fs pulses at a wavelength of 790nm and a repetition rate of 82MHz. Beam 23 yields 0.8W average power and has pulse energies in the nJ range. Beam 23 is split by beamsplitter 25 into a pump beam 27 and a probe beam 29. Eventually, it will be required to bring the probe beam and the pump beam back into synchronisation with one another or change the temporal shift between the pump beam and the probe beam. Therefore, the pump beam 27 is reflected off mirror 31. Thus, the path length of pump beam 27 can be varied. Mirror 31 reflects pump beam 27 through half wave plate 33 and into polariser 35. The polariser 35 transmits the beam onto

mirror 37 which then reflects the beam through lens 39 and cryostat windows (e.g. Spectrosil B) 41 and 43 onto crystal 45. After the beam has passed through chopper 38, the beam is transmitted through lens 39. Crystal 45 is a frequency conversion member and is situated in a magnetic field. Emitter crystal 45 is also angled at 45° to the incident pump beam 27. Chopper 38 functions to chop the beam at a certain frequency. This can improve detection as the beam can be detected at the chopper 38 frequency using a lock-in amplifier. For this type of system, the chopper 38 will preferably be an acousto-optic modulator. Angles of Brewster's angle for the crystal source in question are preferable. For InAs, InSb and GaAs, the Brewster angle is about 70°. Thus, a reflected THz beam 47 is reflected from crystal 45 at an angle of 90° to pump beam 27. The magnetic field generated by a split coil superconducting magnet 49 is parallel to the direction of the emitted THz beam 47. The emitted THz beam 47 is then passed through cryostat window 53 and THz polariser 55.

Figure 2 shows two methods for detecting the THz. The first of these is bolometer 57. This is a He-cooled bolometer which is placed immediately after the cryostat to allow efficient collection of the emitted THz. Bolometer 57 measures both coherent and incoherent contributions to the THz power. In both detection mechanisms, polariser 55 allowed selection of either the transverse electric or transverse magnetic THz polarisation with a 10% transmission loss. Losses by other elements in the THz beam path were determined using an infra red transform spectrometer and accounted for 50% loss at frequencies of 1 THz. The visible pump beam was also attenuated by 19% due to cryostat windows.

Either instead of or in addition to the bolometer, an electro-optic sampling detection mechanism 59 is also present in the apparatus of Figure 2.

The electric-optic sampling system 59 relies on the ac pockels effect. The THz beam 47 is combined with pump beam 29 using mirror 61. Before passing through the back of mirror 61, probe beam 29 is passed through a polariser 63. The combined THz beam 47 and probe beam 29 are then directed onto a 1mm thick (110) ZnTe crystal. Due to the

ac pockels effect, the presence of THz beam 47 causes a rotation in the polarisation of pump beam 29. Therefore, the presence of THz can be detected. When the combined beam 63 has passed through detection crystal 65, it is then transmitted through quarter wave plate 65 to a Wollaston Prism 67 (or other polarisation splitting device) onto balanced photodiode arrangement 69.

If the polarisation of probe beam 29 has not been rotated, the balanced photodiode assembly will read 0. However, if the polarisation of the probe beam 29 has been rotated, there will be a difference in the intensity of the beams split by the Wollaston Prism which are detected by two photodiodes within the balance photodiode assembly 69. The difference in the output of the photodiodes will cause the magnitude of the output of the balance photodiode assembly to be greater than 0. The amount by which the polarisation of the probe beam 29 is rotated by the THz beam 47 is dependent on the intensity of the THz beam 47. Therefore, the output of the balance photodiode assembly 69 directly measures the electric field of the THz beam.

The evolution of the field with time is measured by varying the delay (via mirror 31) between the visible pump 27 and probe beams 29. The power spectrum associated with the THz radiation may be obtained by Fourier transforming the time-domain data. The bandwidth of the THz pulse measured using the electro-optic sampling detector 59 of Figure 2 extends from 0.5 THz to 2.7 THz. This bandwidth is in part constrained by the thickness of the detector crystal and prevents highly accurate measurement of enhancement at frequencies outside this range.

Figure 3a shows the variation in the intensity of the THz signal as the time delay between the probe beam and the pulse beam is varied using mirror 31 for magnetic fields from 0T-8T. Figure 3a shows the results for transverse magnetic polarisation and Figure 3b shows the results of transverse electric polarisation.

Figure 4 shows the THz power measured using the experimental set up of Figure 2 as a function of frequency obtained by Fourier transforming time-domain spectrum of the

type shown in Figures 3a and 3b. An enhancement occurs across the most accessible THz bandwidth, accompanied by a relatively large increase of the power at frequencies above 2.7 THz. The behaviour was also observed for the transverse electric polarisation and was reproduced in spite of the reduced accuracy of detection in this range.

The amount of coherent power can be determined from the area under the frequency of the main power spectrum between 0.5 and 2.7 THz. Calculating this power for both polarisation components, ie. transverse magnetic and transverse electric allows a direct comparison with magnetic field dependence of the bolometer measurements which are shown in Figure 5.

The dependence of the THz power on magnetic field is similar with the electro-optic sampling detector 59 and the bolometer 57 suggesting that the majority of field enhanced emission is coherent. There is a decrease in the intensity of the transverse magnetic polarisation component $B > 6T$ which is not present in the bolometer measurement. This suggests that there may be a peak in the enhancement of a coherently generated THz for this polarisation. Such a peak is not observed in the transverse electric polarisation. These results suggest a further increase in magnetic field B would yield in a larger enhancement of the coherently generated THz power.

Figure 6 shows the dependence of the bolometer power on magnetic field for both of the individual polarisation components (i.e. transverse electric and transverse magnetic) as well as the total value. It can be seen that if the magnetic field is increased, both polarisation components are also increased. The total power is 486mW at 8T after accounting for losses in both the cryostat and the polariser. Path lengths between the cryostats outer window and the bolometer were kept less than 5cm to minimise atmospheric absorption of the THz. Therefore, with an average incident pump power at the sample of 113mW, the average power visible to average THz power conversion efficiency is 0.43%.

These results clearly suggest that going to even higher magnetic fields will result in even higher THz efficiency.

Figure 7 shows results taken at 8T and 180K for (100)InAs as a generator crystal. Sample geometry is the same as that described with reference to Figures 1 and 2.

The x-axis shows the variation in the visible pulse energy of the pump beam. The left-hand y-axis shows the visible THz conversion efficiency and the right-hand y-axis shows the measured THz pulse energy. The open symbols shows the energy for an unamplified, conventional oscillator source, and the closed symbols show those for an amplifier system. The lines through the closed symbols and the open symbols relate to a double exponential fit to the results. This graph suggests that increasing the visible pulse energy does not necessarily provide an increase THz signal. Therefore, other methods of increasing the THz signal are of commercial significance.

Figures 8a and 8b compare results taken in accordance with an embodiment of the present invention. With those of the known prior art. Specifically, the data points A to J are as follows:

- A. 1mm (110) ZnTe at room temperature, with no magnetic field. Pumped with 100mW from an oscillator.
- B. (100) InAs at 173K and $B=8T$, applied parallel to the direction of the THz beam. Pumped 130mW average power from an oscillator in accordance with an embodiment of the present invention.
- C. (100) InAs at 173K and $B=8T$, applied parallel to the direction of the THz beam.

Pumped 83mW average power (0.33 μ J pulse energy) from an amplifier in accordance with an embodiment of the present invention.

- D. (100) InAs at room temperature and $B=1.7T$, applied perpendicular to the direction of the THz beam. Pumped with 1.5W from an oscillator. (Sakura et al, J. App. Phys. 84 654).
- E. Large aperture photoconductive antenna on SI GaAs at room temperature, no magnetic field. Pumped with 882mW (4.4 μ J) from an amplifier. (Mouret et al Microwave Opt. Tech. Lett. 17 23).
- F. Large aperture photoconductive antenna on SI GaAs at room temperature, no magnetic field. Pumped with 500mW (500 μ J) from an amplifier. (Budiartha et al IEEE J. Quant. Elec. 32 1839).
- G. Large aperture photo conductive antenna on SI GaAs at room temperature, no magnetic field. Pumped with 2.8mW (282 μ J) from an amplifier. (You et al Opt. Lett. 18 290).

Figure 9 shows a compact emitter in accordance with an embodiment to the present invention. The emitter comprises an electro magnet or a permanent magnet 71 which has a hole 73 formed therethrough. Hole 73 completely penetrates the magnet 71 and defines a space for the THz emitter space. The space is boarded on four sides by magnet 71 and at the upper 78 and lower 77 surfaces by non-magnetic material. The visible pump beam 75 enters the lower surface 77 of the emitter space 73. The pump beam 75 enters the emitter through pump window 79. The pump beam 75 is reflected off mirror 81 onto emitter crystal 83. The emitter crystal is angled with respect to the magnet and the incident beam 75 so that the emitted THz 85 is parallel to the direction of the magnetic field. The THz 85 is transmitted through THz window 87 which is located in the upper surface 78 of emitter space 73.

Figure 10 shows a variation on the emitter of Figure 9. The same reference numerals are used to denote the same features in both Figures 9 and 10. Therefore, these features will not be repeated here. The compact emitter here is capable of being cooled to very

low temperatures. To achieve this cooling, the crystal 83 is mounted on a Peltier cooling element 89. The emitter space 73 has a vacuum port 91 such that the air within the emitter space can be evacuated.

Figure 11 shows a further variation on the compact emitter structure of Figures 9 and 10. Again, the description of like features will not be repeated. The detection crystal 83 is mounted on an electro magnet or a permanent magnet 93. The electro magnet or permanent magnet causes a magnetic field which is normal to the surface of the emitter crystal 83. The THz beam 85 is again produced by refraction of the pump beam 75 of the surface of the semiconductor emitter crystal 83. The angle of incidence of the pump beam 75 is chosen so that there will be a component of the magnetic field in the direction of the THz beam output 85.

The geometry in these and other figures is also chosen such that the angle of incidence of the pump beam qB is Brewster's angle for the crystal in question.

Figure 12 shows a further variation on the compact emitter structure. As for Figure 9, an electro magnet or permanent magnet 71 is formed with an aperture 73 which provides a sample space. The aperture is bounded at a lower surface 72 and an upper surface 74 by material which is not part of the magnet 71. A THz window 87 is formed in the upper surface of the bounding material 74. A hole 95 is formed in a side wall of the magnet 73. This hole forms a channel for the visible pump beam 75. The hole is positioned such that the visible pump beam can be shone through the hole directly onto emitter crystal 83 without the need of mirrors within the compact emitter itself. The reflected THz beam 85 is transmitted from the compact emitter through THz window 87.

Figure 13 shows a further variation on the emitter of Figure 12. Here, as described with reference to Figure 10, the crystal 83 is mounted on Peltier cooling element 89. The emitter space defined by aperture 73 must be evacuated. Therefore a vacuum port 91 is provided on a lower surface 77 of the compact emitter. The visible pump beam is again

introduced into the compact emitter along channel 95. The pump beam entering the emitter is sealed with a window or lens 97.

Figure 14 shows a THz emitter in accordance with a further embodiment of the present invention. The relationship between the input beam and the output beam with respective surface normal of the same as described with references to Figure 1. Therefore, these features will not be repeated. However, the THz emitter crystal is different in Figure 14 to that of Figure 1. In Figure 14, the THz emitter crystal (101) is imbedded with magnetic ions Mn^{2+} . The strong S-D exchange interaction between the electron spins and the imbedded Mn^{2+} ions is known to amplify the frequency of the electron spin precession under the applied magnetic field. This results in field tuneable oscillations in the magnetic component of spin. It is known that these oscillations occur at THz frequencies. The frequencies given by the spin split energy $g\mu B$ where B is the applied magnetic field and μB is the Bohr magneton. The increase in energy owing to the presence of interactions between carriers and the magnetic ions is given by the enhanced value of the g factor, which ranges from 2 in non-magnetic samples all the way to 430 or larger in magnetic samples. It is believed that enhanced g -factors may result in accelerations associated with electron spin of the radiated $g\mu B$ in the THz range. In Figure 14, the magnetic field is arranged perpendicular to the surface normal and photo injected carrier spins.

Another mechanism for enhanced Terahertz emission from magnetically doped semiconductors is the enhanced internal magnetic field associated with the ions, which leads to further acceleration of charge in the semiconductor and hence higher Terahertz emission powers. With the application of a small external magnetic field (e.g. several hundred millitesla, readily achieved with permanent magnets), the moments of the Mn^{2+} ions are aligned.

One motivation for introducing magnetic ions into the semiconductor is to reduce the magnetic fields required for THz enhancement from the several Tesla values suggested above, which may require superconducting magnets, to $B < 2T$ achievable with

permanent or electromagnets. Moreover, even in semiconductors where significant enhancement of the visible to THz conversion efficiency occurs at low magnetic fields, the addition of magnetic ions will further enhance the field, and hence conversion efficiency, achievable. To see this, note the net field inside a magnetically-doped semiconductor is given by

$$B_{\text{net}} = B_{\text{applied}} + \mu_0 M_{\text{Mn}}$$

where B_{applied} is the externally applied field inside the semiconductor (denoted simply by B in the preceding discussion). μ_0 is the permeability and M_{Mn} is magnetization associated with the ions; thus $B_{\text{ion}} = \mu_0 M_{\text{Mn}}$ is the magnetic field in the semiconductor in the presence of the magnetic ions.

The ultrafast laser sources can be those described. The laser must operate at frequencies at or above the band gap of the material in order to create photocarriers. Circular polarisation of the pump beam is generally required, achieved using standard quarter wave plates, if the spin of the photocarriers is to be oriented parallel to the surface normal.

The magnetically doped may be fabricated in a number of ways:

Numerous types of magnetically doped frequency conversion members 101 are possible. Bulk $\text{Zn}_{1-x}\text{Mn}_x\text{Se}$ grown on $\langle 100 \rangle$ GaAs or other compatible substrates are one class of structure. $x=0$ to 0.1 have been studied using optical and ESR characterization techniques, but higher concentrations x are possible using MBE.

(Ga,Mn)As bulk layers are other systems for realising internal magnetic fields to supplement the externally applied field. (Ga,Mn)As can be grown on (001) GaAs substrates using techniques such as low temperature MBE. For example, 100nm GaAs buffer layers may be grown at 570 C, followed by 0.2mm $(\text{Al}_x\text{Ga}_{1-x})\text{As}_{0.8}$ etch stop layer for any processing and mesa isolation. This layer is grown at 670 C. Finally, a

2mm (Ga,Mn)As layer is grown. Typical Mn concentrations are in the range 0.043, although other concentrations are possible using MBE.

ZnCdSe/ZnSe quantum wells on <100> GaAs having different concentrations of Mn²⁺ form an important class of structures. Discrete fractional monolayer planes of the binary magnetic semiconductor MnSe are incorporated into the ZnCdSe wells. The quantum well region thus consists of monolayers of the randomly diluted quaternary alloy (ZnCd,Mn)Se separated by nonmagnetic layers of say Zn_{0.8}Cd_{0.20}Se. The introduction of magnetic ions into the crystal lattice greatly enhances the effective g factors of the electron and hole bands through strong spin sensitive J_{sp-d} exchange interaction between the s-like (p-like) conduction (valence) band and the local 3d electrons that comprise the spin-5/2 paramagnetic Mn²⁺ moment. There are advantages to various distributions of the magnetic ion layers in the quantum wells. For example, for a fixed number of Mn spins, the g-factor may be enhanced by spreading the distribution of MnSe from a single, thick layer placed at one position in the ZnCdSe well, to several layers distributed in different planes throughout the well. This also mitigated against dephasing phenomena due to ion-ion interactions.

Figure 15 shows an experimental arrangement for measuring THz output from a magnetically doped semi-conductor. As many of the features are the same as described in reference to Figure 2, these will not be repeated. The main variation on the equipment of Figure 2 is the variation in the orientation between the magnetic field and the emitted THz. Here, the pump beam is transmitted onto a magnetically doped semiconductor crystal emitter in the direction parallel to the surface normal of the semiconductor crystal emitter. The magnetic field B is arranged so that it is parallel to the surface of the semi-conductor crystal emitter. The THz beam (57) is emitted parallel to the surface normal of the emitter. The beam (47) is then reflected off beam-splitter (121) which reflects the THz-beam onto mirror (123) and into the electro-optic sampling unit (59). The beam-splitter (121) allows transmission of the pump beam onto the cryostat window. The beam splitter may be a suitable material such as cellulose nitrate,

mylar, or other materials that are ideally non-lossy and non-dispersive at both THz and visible/near-infrared frequencies.

Figure 16 shows a further embodiment of the present invention. Here, an external bias is applied via contacts 201) and 203 across the surface of the THz emission crystal 205. The THz emission crystal 205 can be any of the type previously described. It may also be a magnetically doped structure.

The incident pump beam 207 then impinges on the emitter 2 or 5 in the region between the two contacts 201 and 203. The bias between the two contacts causes a lateral photocurrent to arise. The magnetic field 209 is incident on the sample at an angle of θ (theta) so that the emitted THz experiences a component of the magnetic field. The THz may be emitted via refraction or transmission through the sample 205.

Contacts 201 and 203 may take many forms. For example, as shown in Figure 16a, the contacts may be regular, rectangular contacts. However, as shown in Figure 16b, the contacts may be made in the shape of a bow tie antenna.

The contacts 201 and 203 may be Ohmic contacts. The distance between the two contacts may be varied between several microns to several millimetres.

Figure 17 shows a further arrangement used to enhance the field at the surface to enhance THz emission. Figure 17a shows an experimental arrangement similar to that of Figure 1. However, here, the emitter crystal has a front gate 301 located on the surface on which the pump beam impinges. The front gate 301 is a Schottky gate, the gate acts to modify the shape of the surface field in the semiconductor to enhance the THz emission. The gradient to the surface field enhances carrier acceleration at the surface and this enhances THz emission.

Typically, the gate will be fabricated from Au, NiCr etc.

The previous embodiments have mainly concentrated on enhancing the THz output by increasing the acceleration of the charged carriers in the frequency conversion member by using techniques such as applying an electric field to the surface of the frequency conversion member, using magnetic dopants etc.

However, it is possible to also enhance the THz emission by careful choosing of the applied magnetic field and the free carrier concentration which is controlled by the optical fluence of the input beam.

Figure 18 shows a measurement from a source which comprises a undoped GaAs frequency conversion member, the incident radiation surface is (100). the optical fluence is varied from 50 to 900nJ/cm². The plot of Figure 18 is a logarithmic plot in both the x and y directions (Fluence of input beam and Power of emitted beam respectively).

The data is shown for four values of magnetic field: 2T (empty circles); 4T (solid circles); 6T (triangles) and 8T (squares). The 4T data has been fitted (as will be explained below) and is shown by the solid line. The plot demonstrates the cross over between the low fluence regime (where the data fits to the solid line) and the high fluence regime (where the data diverges below the solid line).

The scattering length of the free carriers in the frequency conversion member increases with applied magnetic field due to charge executing a larger portion of cyclotron orbit before scattering off in adjacent electron or other particles. Cyclotron orbits are given by the well known classical formula in one, two or three dimensions and depend on both the optically induced (pump-induced) carrier density n as well as the applied magnetic field B and the material dependent effective mass of the accelerated charge m .

Figure 18 shows the cross over from the low optical fluence limit to the high optical fluence regime. In the low regime, carrier-carrier scattering is the dominant mechanism which limits the enhancement of THz power and one set of design procedures is used.

In the high fluence limit, the screening of the electric field is the dominant mechanism limiting the enhancement of THz power.

In the presence of a fixed magnetic field such as one might find in a superconducting magnet in persistent mode (the type found for example in MRI machines) or a fixed permanent magnet, one of the best ways to determine the limit of the optical fluence is to plot out the experimentally measured THz power as function of adjusted optical fluence (determined by laser power and/or spot size adjustment, or other means). Along with this, one plots the relation which governs emitted power in the presence of carrier-carrier scattering. The time-averaged emitted power can be approximated with the expression:

$$P \propto \frac{n^2 B^2}{m^4} \left[\frac{\cos \theta_M \sin \theta_M}{2\theta_M} + \frac{1}{2} \right], \quad (1)$$

where P is the power of the emitted beam, n is the free carrier concentration, m is the effective mass of the carriers, B is the magnetic field and θ_M represents the angle completed by the carrier at the time of the collision, and r is the cyclotron radius. This angle can be expressed as a function of the ratio $R=\lambda/r$ of the characteristic radius as

$$\theta_M = \arccos \left[1 - \frac{1}{2} \left(\frac{\lambda}{r} \right)^2 \right], \quad (2)$$

which is only valid for $(\lambda/r) < \sqrt{2}$. For magnetic fields B smaller than 10T, (2) can be approximated as a linear function of B, $\theta_M \approx \alpha B$. In this limit, (1) reduces to

$$P \propto \frac{1}{m^4} x \left[\frac{B \sin(2\alpha B)}{4\alpha} + \frac{B^2}{2} \right] \quad (3)$$

Comparing the Terahertz power P (1) as function of optical fluence (or equivalently, photogenerated carrier density n in (1)) with the experimental determination noted above allows one to determine whether one is in the low or high optical fluence limit.

In the low fluence limit the experimental data can be made to lie along the same line as that derived from (1) with a suitable multiplicative factor applied to one or the other data set. In the high fluence limit, there is significant deviation of experimental data below the prediction of (1) at higher optical fluences, whereas at lower fluences the lines coincide.

Put more succinctly, to determine the fluence limit, one first measures experimentally determined powers as a function of fluence and then fits them to (1), with weight given to the points at low fluence.

Figure 18 shows such a fit for $B=4T$. The fluence value at which divergence (expt data falls below predictions of (1)) between (1) and the experimental data occurs marks the boundary; fluences below this are in the low fluence limit, and fluences above it are in the high fluence limit.

In Figure 18, this occurs near fluences of 400 nJ/cm^2 for $B=4T$ in the case of GaAs. Figure 18 also demonstrates how the limit will vary with the value of B applied. The limit in which the system falls will be determined by the magnetic fields B provided by available magnets, and range of laser fluences available with the ultrafast laser. Choice of material system and its characteristics will also play a role.

Scattering is believed to be the main mechanism which is responsible for controlling the emitted THz power. Practical limits are also imposed by the availability of fields using permanent magnets and the high cost associated with superconducting magnets, which rises with magnetic field. The electron-electron scattering will reduce THz power appreciably until the limit where the cyclotron diameter is comparable to the electron-electron scattering length, i.e. $2r$ is preferably equal to, but may be less than the electron-electron scattering length $\lambda = n^{-1/3}/2$.

As both the cyclotron diameter and the electron-electron scattering length are dependent on B and n (optical fluence), these need to be optimised simultaneously. The design rule

therefore is to choose a magnetic field for a given fluence (or fluence for given magnetic field) such that $2r \sim \lambda$. Scattering between adjacent electrons result in decoherence of the Terahertz waveforms emitted by those accelerated electrons and hence reduced Terahertz power. Decoherence here means that the emitted waveforms from the accelerated charge do not add or combine constructively, i.e. no constructive interference.

In general, electron-electron (or more generally carrier-carrier) scattering is the dominant mechanism at low optical fluences, leading to low photogenerated carrier densities. The design rule above ensures that the length of the electron trajectory s is maximised before scattering off the next adjacent electron located λ away. This is shown schematically in Figure 19. In Figure 19, the direction of THz beam (the emitted beam k_{THz}) is into the page and the magnetic field B is perpendicular and out of the page. The plane of the cyclotron orbit is within the plane of the page.

Figure 20 illustrates the calculated cyclotron radius for values of magnetic field (2T, 4T, 6T and 8T) against optical fluence (solid lines). The mean free path for an optical fluence of 20 nJ/cm^2 , is shown as a weak dotted line.

For an optical fluence of 20 nJ/cm^2 , the intersection of the $\lambda(n)$ vs. n (weak dotted line) and $r(n)$ vs. n (solid lines) suggests that $B=6\text{ T}$ is the optimal field, e.g. compromise between reducing electron-electron scattering and thereby maximising power with higher field (hence longer mean free path s) and the practicalities and cost of high magnetic fields.

Figure 21 shows a plot of THz radiation from (100) GaAs measured by a bolometer as a function of the applied magnetic field ($T=200\text{ K}$). Circles, triangles and dashed line represent TE, TM-polarised and total emitted power respectively. Crosses are rescaled EOS data (THz field amplitude squared). Solid line is a fit to TE data (circles) with equation (3).

It is often desirable to use a high fluence as, under many types of conditions this will give the highest output power. However, in the high fluence regime, screening of the surface field becomes the dominant mechanism, and the term E_{surf} is dramatically reduced. This means that the efficiency of the source reduces even though the power of the emitted beam increases with the power of the input beam.

The effect of fluence on surface field is illustrated in Figure 22, where the surface field is plotted as a function of depth into the semiconductor from the surface of the sample. The plots were done using a Monte Carlo simulation. The results suggest that in the high fluence limit, screening of the surface field is reduced - and THz power enhanced - with the application of magnetic field. The results suggest that this is valid for time scales from $t=0$ to $t=2ps$, where $t=0$ is when the Terahertz pulse is received at the detector.

Figure 23 is a plot of the values of the input beam fluence where the fluence crosses from the low regime to the high regime for 5 different magnetic field values (0T, 2T, 4T, 6T and 8T).

This data was found to fit the general exponential function:

$$F=F_0+A\exp(B/t)$$

where F is the fluence of the input beam, B is the magnetic field and F_0 , A and t are fitting parameters. In this particular example, $F_0=70$, $A=56$ and $t=5.7$.

Thus, the boundary between the low and high fluence regimes increases exponentially with increasing magnetic field.

The fluence measurements were taken from the data of Figure 18 where the experimentally measured THz power drops approximately 10% below the linear fit of (1) to the low fluence data. Thus, when dealing with high fluences, it is desirable to

choose a magnetic field such that the source is on the boundary between the low and high fluence limits. Similarly, the optical fluence can be adjusted for a given magnetic field so that it lies on the line of Figure 23.

By way of example, Figure 23 shows the optimal magnetic field ($B=4.7\text{T}$) for a set laser fluence of 200nJ/cm^2 .

CLAIMS:

1. A radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam with a frequency different to that of the emitted radiation, the source being subjected to a magnetic field wherein the free carrier concentration of the frequency conversion member and the applied magnetic field is configured such that the cyclotron diameter of the free carriers of the frequency conversion member is within 30% of their scattering length.
2. A radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam having a frequency different to that of the emitted beam of radiation, the source being subjected to a magnetic field, the magnetic field and fluence of the input beam being configured to minimise the screening effect of free carriers in the frequency conversion member.
3. A radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam with a frequency different to that of the emitted beam, the frequency conversion member comprises a magnetic material dopant.
4. A radiation source according to claim 3, wherein the dopant is Mn.
5. A radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to being irradiated with an input beam with a frequency different to that of the emitted beam, the source being subjected to a magnetic field, the source further comprising means for applying an electric field at the surface of the frequency conversion member which is irradiated by the input beam.

6. A radiation source according to claim 5, wherein the means for applying an electric field comprise a pair of Ohmic contacts provided to the frequency conversion member and means for applying a potential difference across said Ohmic contacts.
7. A radiation source according to claim 5, wherein the Ohmic contacts have a substantially triangular shape such that the contacts taper towards one another.
8. A radiation source according to claim 5, wherein the means for applying a field comprises a Schottky gate provided on the surface of the frequency conversion member which is irradiated by the input beam.
9. A radiation source according to any preceding claim, wherein the input beam is circularly or elliptically polarised.
10. A radiation source according to any preceding claim, wherein the magnetic field has a component parallel to that of the emitted beam.
11. A radiation source according to any preceding claim, wherein the emitted beam is produced by reflection of the input beam off a surface of the frequency conversion member.
12. A radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam with a frequency different to that of the emitted radiation, the source being subjected to a magnetic field which has a component parallel to that of the emitted beam of radiation, the emitted beam of radiation being produced by reflecting the input beam off a surface of the frequency conversion member.
13. A radiation source according to any preceding claim, wherein the magnetic field is oriented parallel to the emitted beam.

14. A radiation source according to any preceding claim, wherein the magnetic field is oriented at an angle of at most 20° to the emitted beam.
15. A radiation source according to any preceding claim, wherein the frequency conversion member is selected from InAs, InSb and GaAs.
16. A radiation source according to any preceding claim, configured such that the angle between the input beam and the surface normal of the frequency conversion member is substantially the Brewster angle
17. A radiation source according to any preceding claim, wherein the frequency conversion member is subjected to a magnetic field of at least 2T.
18. A radiation source according to any preceding claim, the source further comprising a magnet to apply the said magnetic field.
19. A radiation source according to any preceding claim, wherein the emitted radiation comprises at least one frequency in the ranges from 0.1 THz to 100THz.
20. A radiation source according to any preceding claim, wherein the input beam is a pulsed beam.
21. A method of optimising a radiation source, the radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam with a frequency different to that of the emitted radiation,
the method comprising the step of applying a magnetic field to the source, the magnitude of the magnetic field being chosen in order to minimise the screening of the surface field of the frequency conversion member by free carriers in the frequency conversion member for a predetermined fluence of the input beam.

22. A method of optimising a radiation source, the radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation in response to irradiation with an input beam with a frequency different to that of the emitted radiation,

the method comprising the step of applying a magnetic field to the source, the fluence of the input beam being chosen in order to minimise the screening of the surface field of the frequency conversion member by free carriers in the frequency conversion member for a predetermined magnitude of the applied magnetic field.

23. A method according to either of claims 21 or 22, wherein the magnitude of the applied magnetic field or the optical fluence is determined by the steps of:

- a) measuring the power of the emitted beam as a function of optical fluence for at least three values of magnetic field;
- b) fitting the data measured in a) to the relation:

$$P \propto \frac{n^2 B^2}{m^4} x \left[\frac{\cos \theta_M \sin \theta_M}{2\theta_M} + \frac{1}{2} \right], \quad (1)$$

where P is the power of the emitted beam, n is the free carrier concentration, m is the effective mass of the carriers, B is the magnetic field and θ_M is :

$$\theta_M(n, B) = \arccos \left[1 - \frac{1}{2} \left(\frac{\lambda}{r} \right)^2 \right], \quad (2)$$

where λ is the mean free path which is defined as $1/2(n^{-1/3})$ and r is the cyclotron radius;

c) determining the fluence values for the at least three values of magnetic field where with increasing fluence the measured power starts to diverge from the function of step b); and

d) fitting an exponential function to the at least three values determined in point c) such that the optimum fluence can be determined for a given magnetic field or an optimum magnetic field can be determined for a given fluence.

24. A radiation source as substantially hereinbefore described with reference to any of the accompanying drawings.

25. A method of optimising a radiation source as substantially hereinbefore described with reference to any of the accompanying drawings.

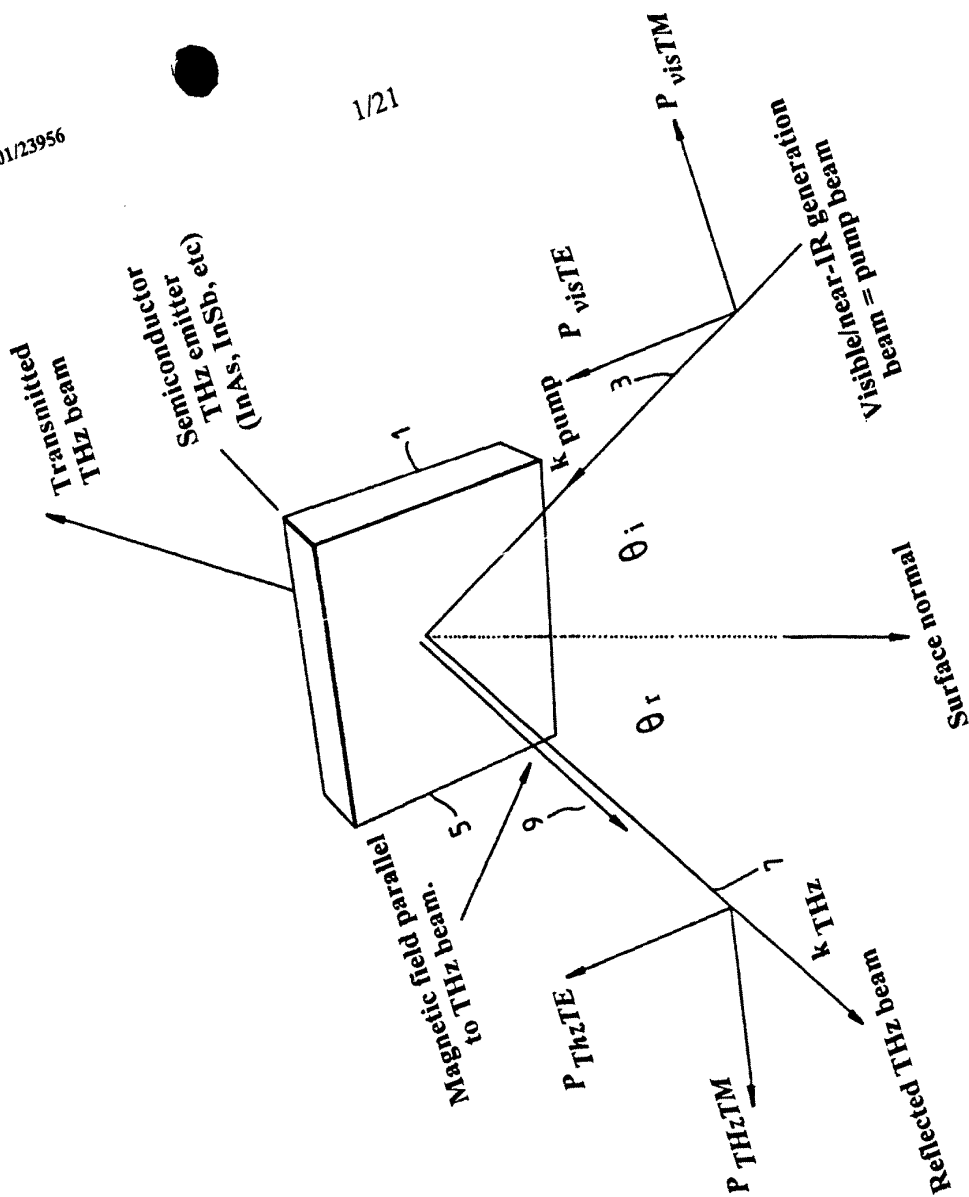


Fig. 1

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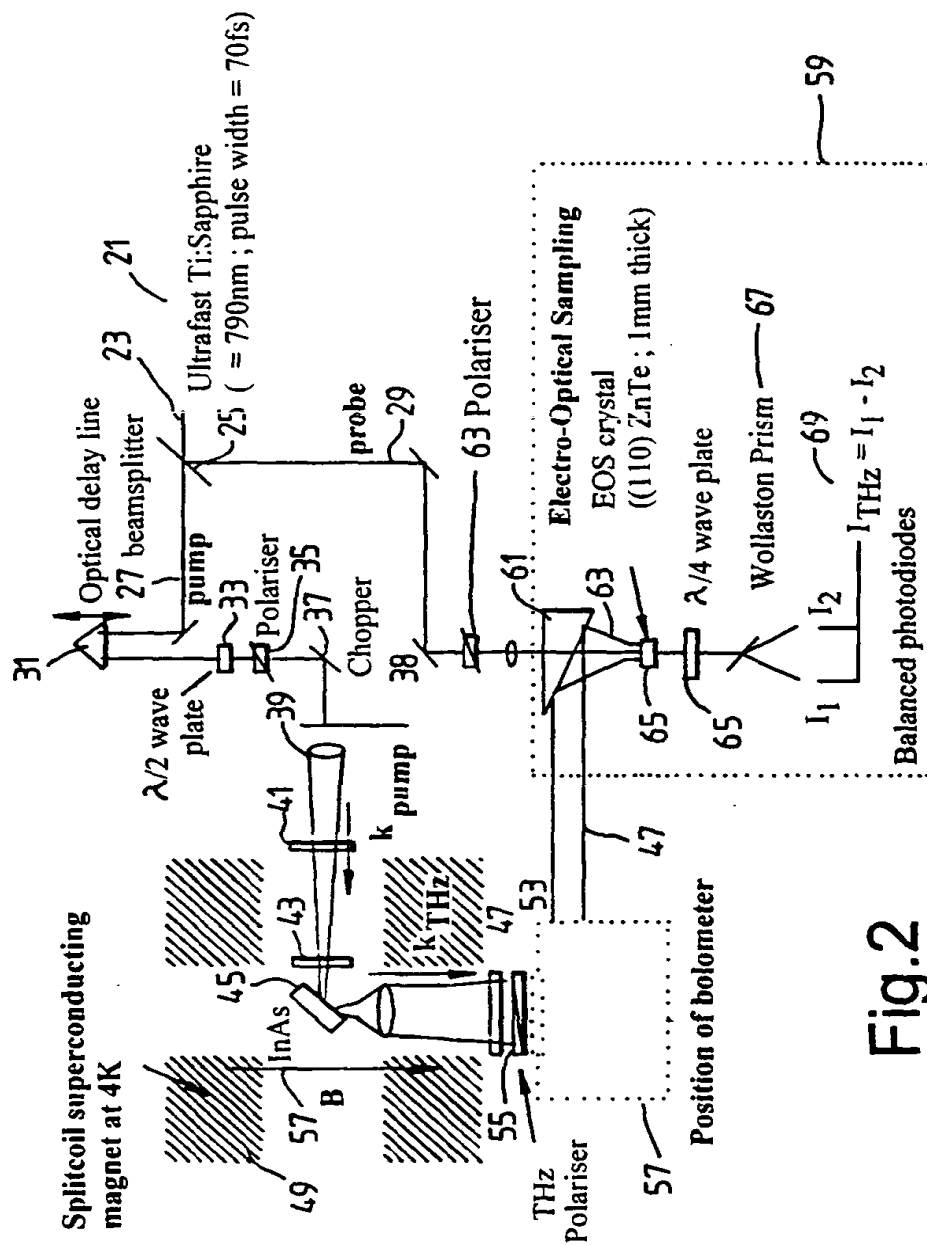


Fig.2

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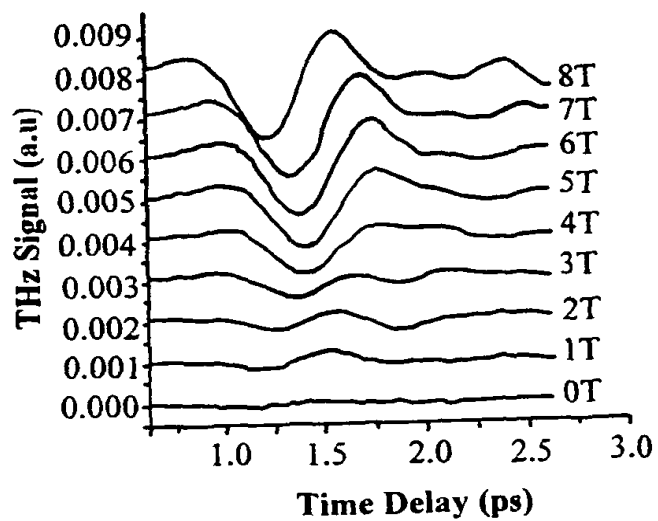
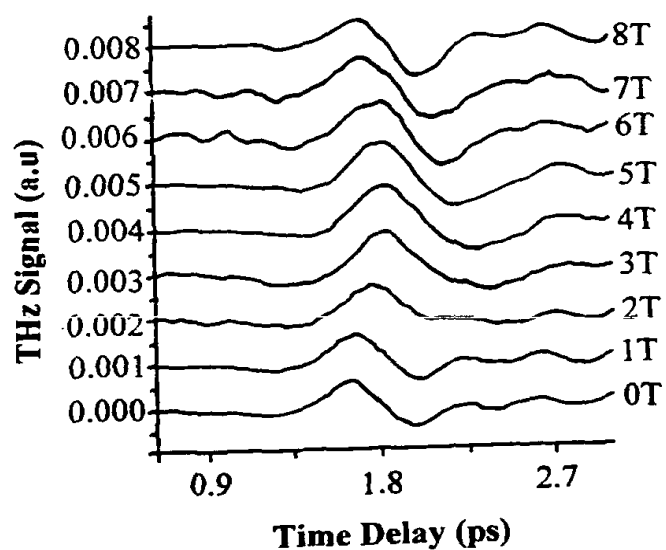


Fig.3

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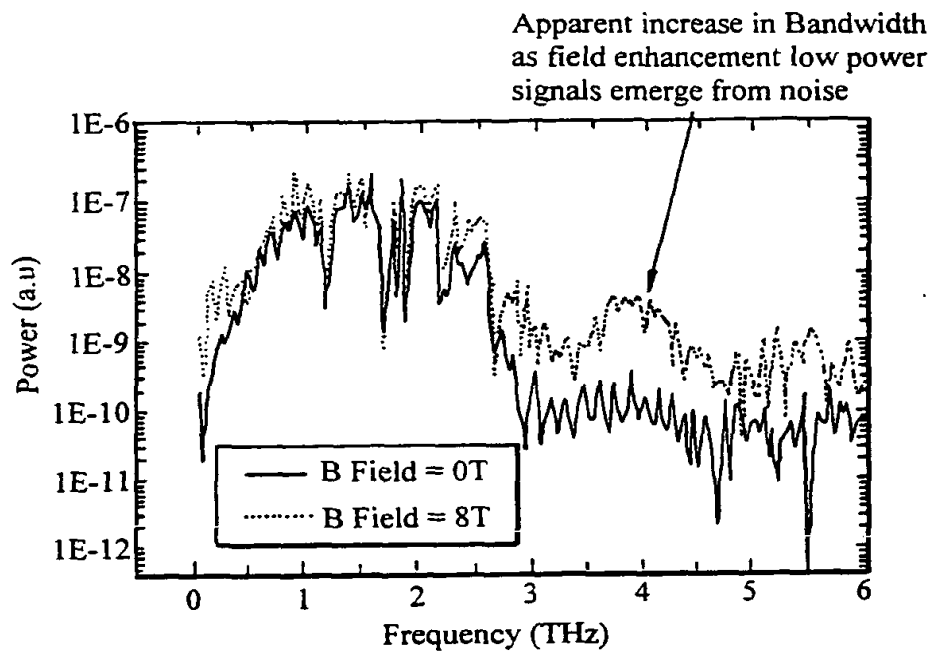


Fig.4

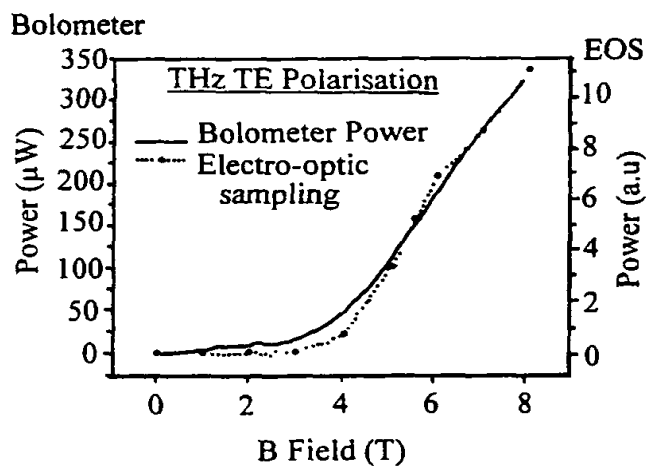


Fig.5

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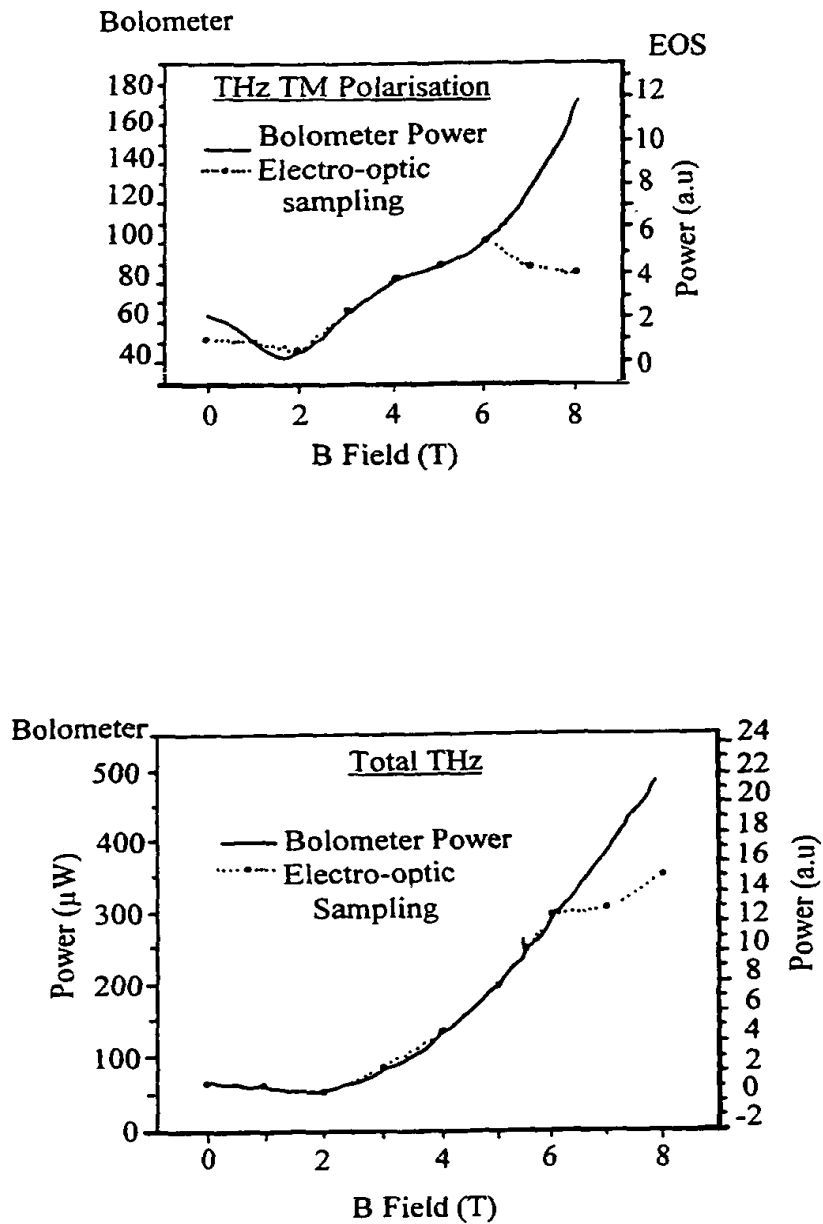


Fig. 5(cont'd)

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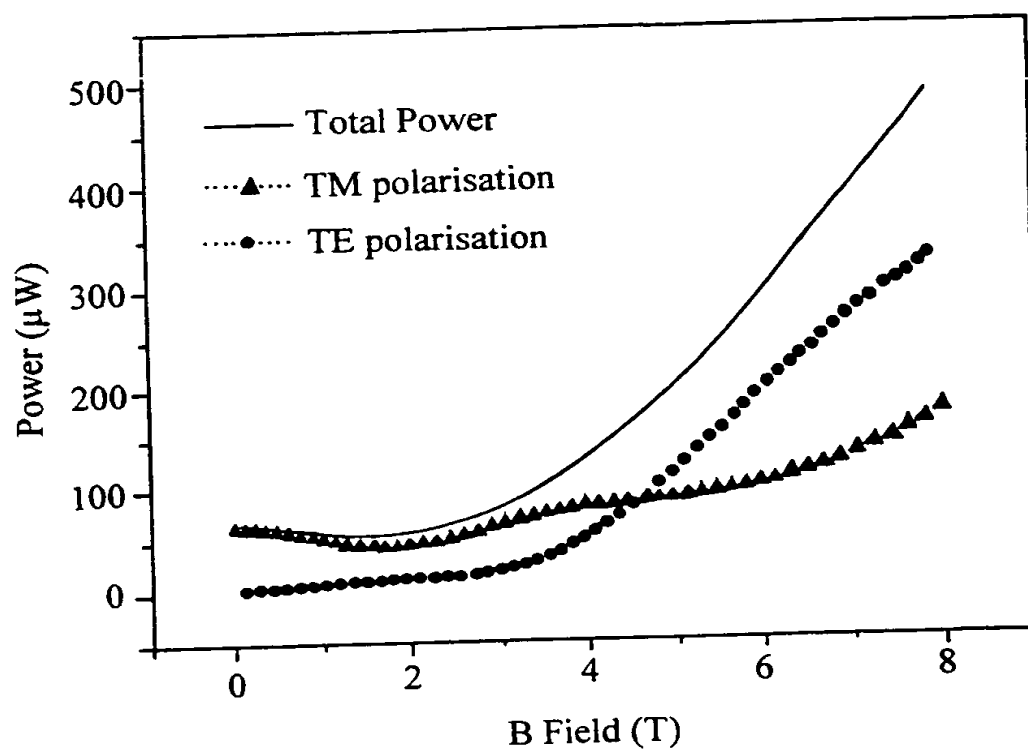


Fig.6

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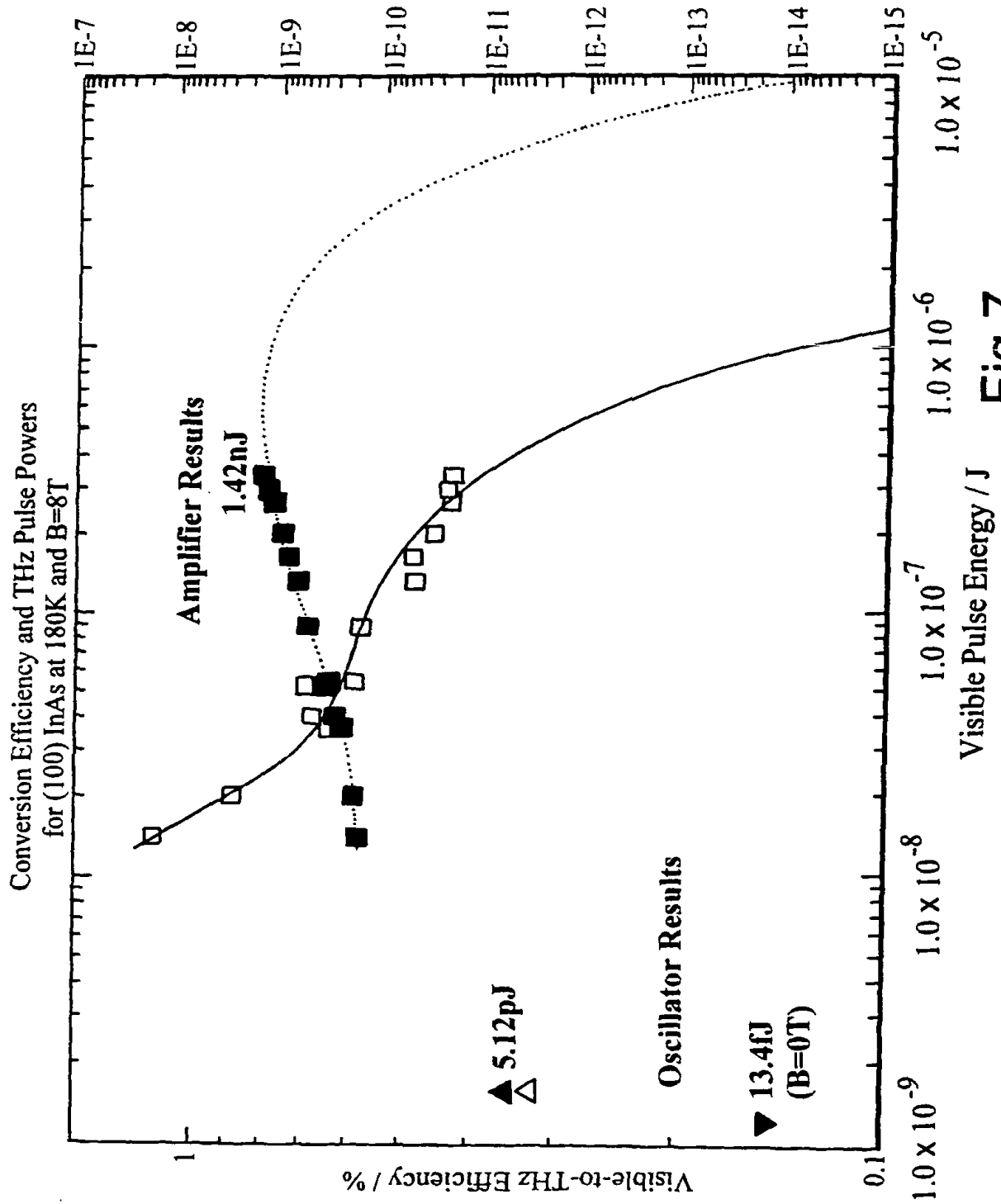


Fig.7

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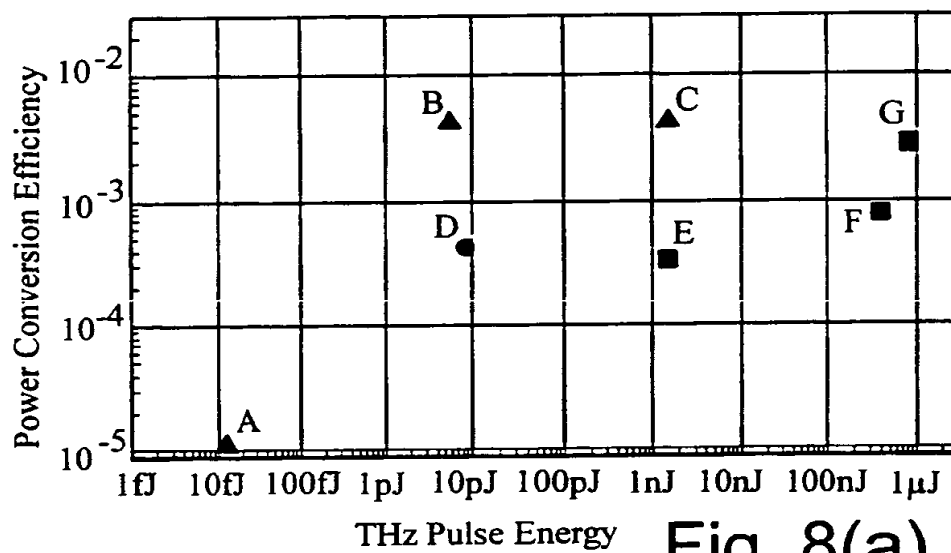


Fig. 8(a)

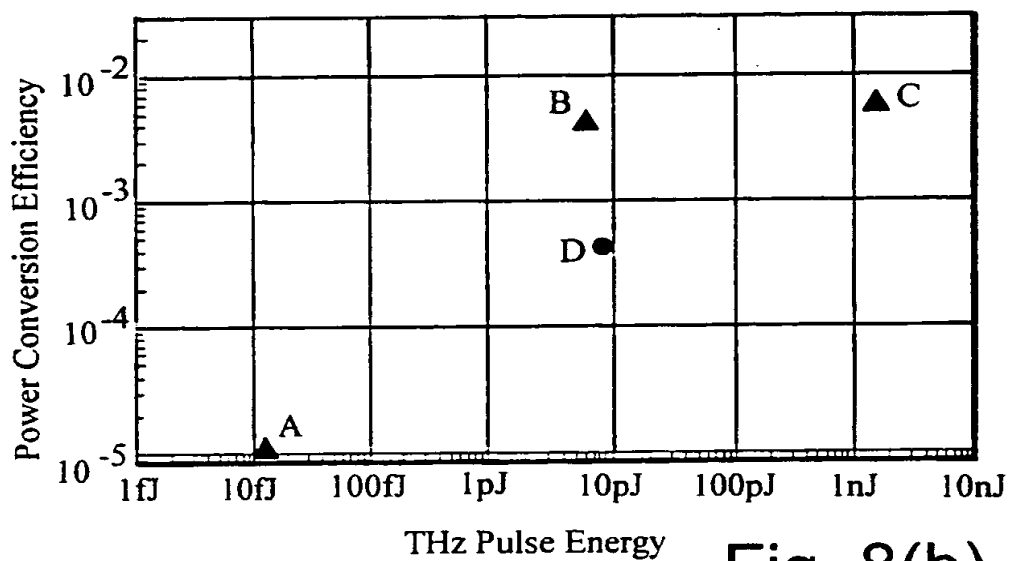


Fig. 8(b)

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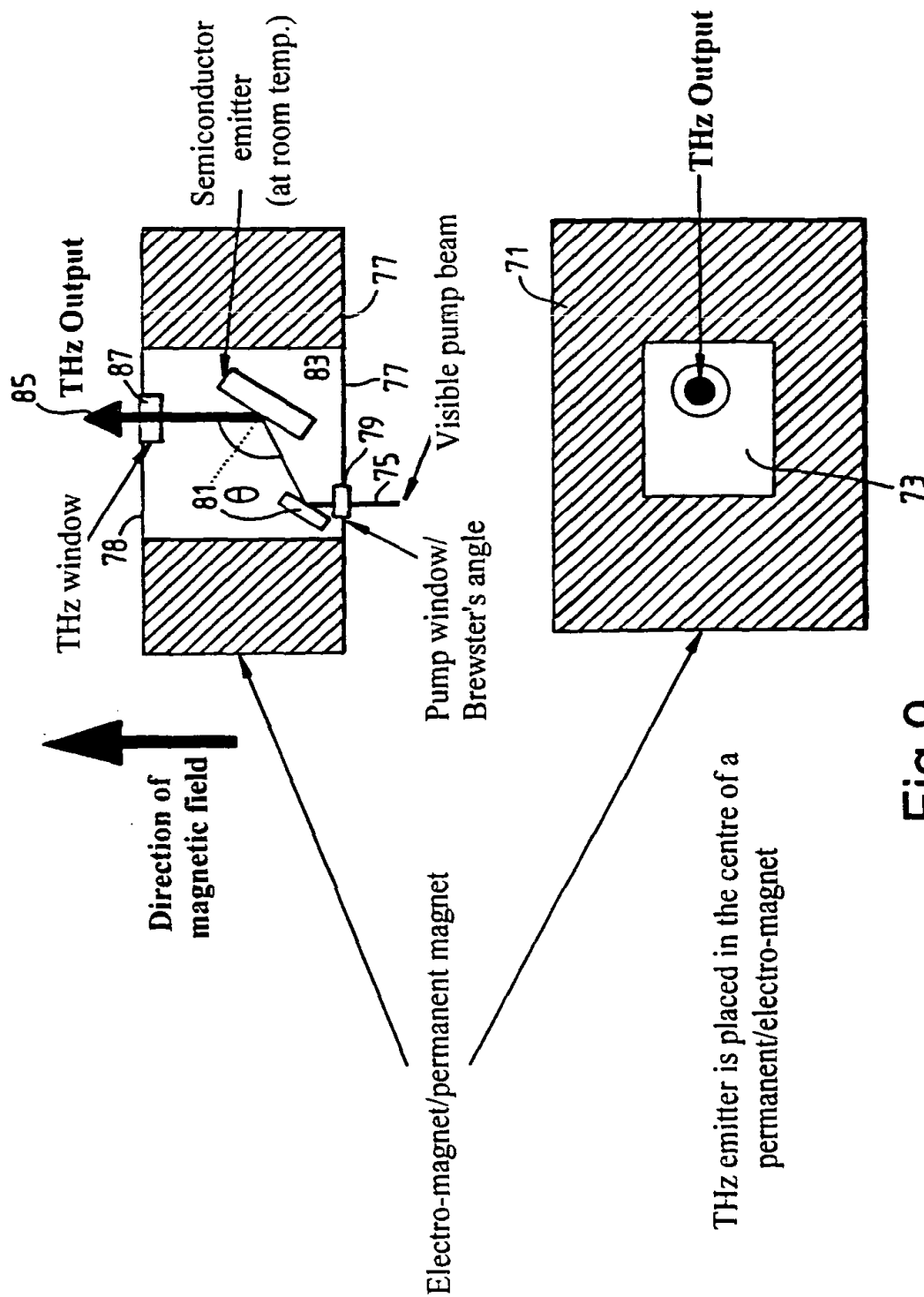
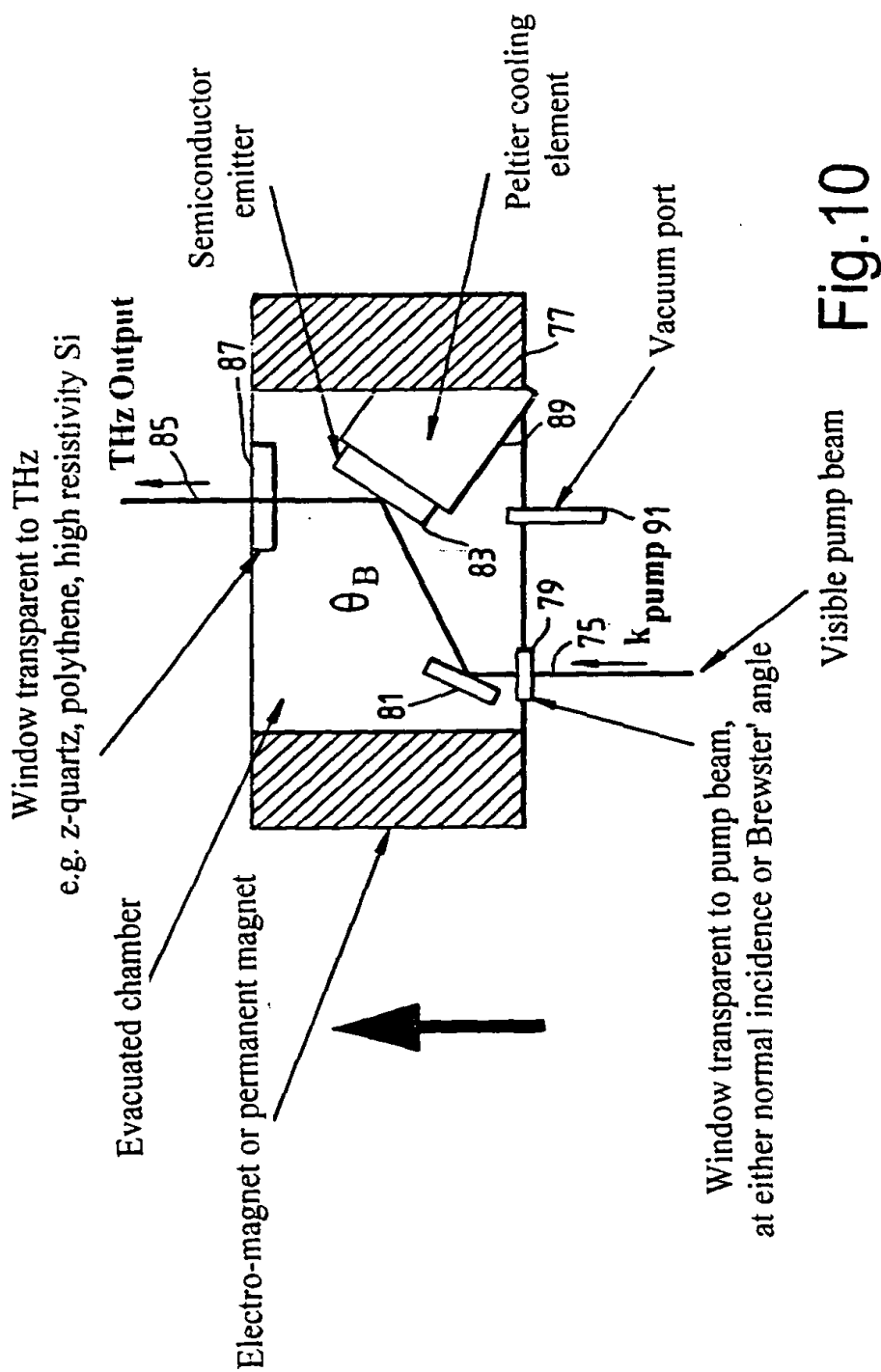


Fig.9

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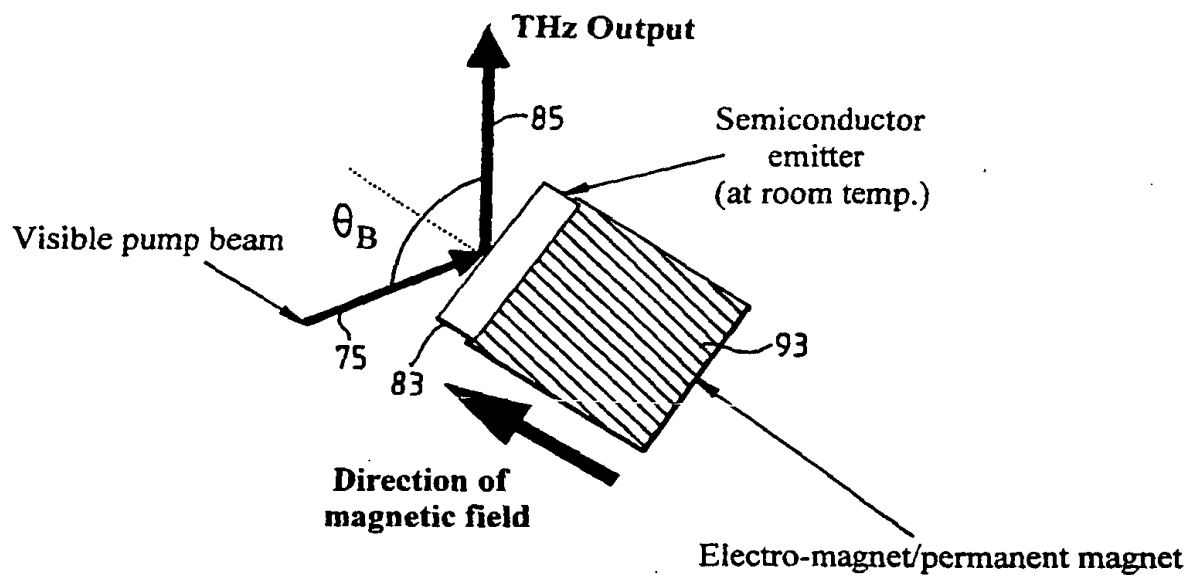


Fig.11

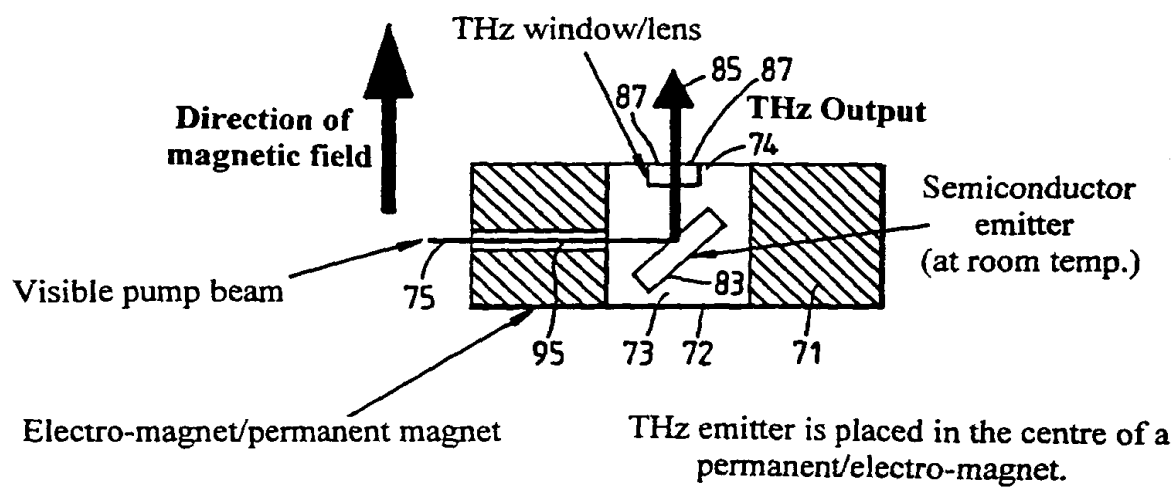


Fig.12

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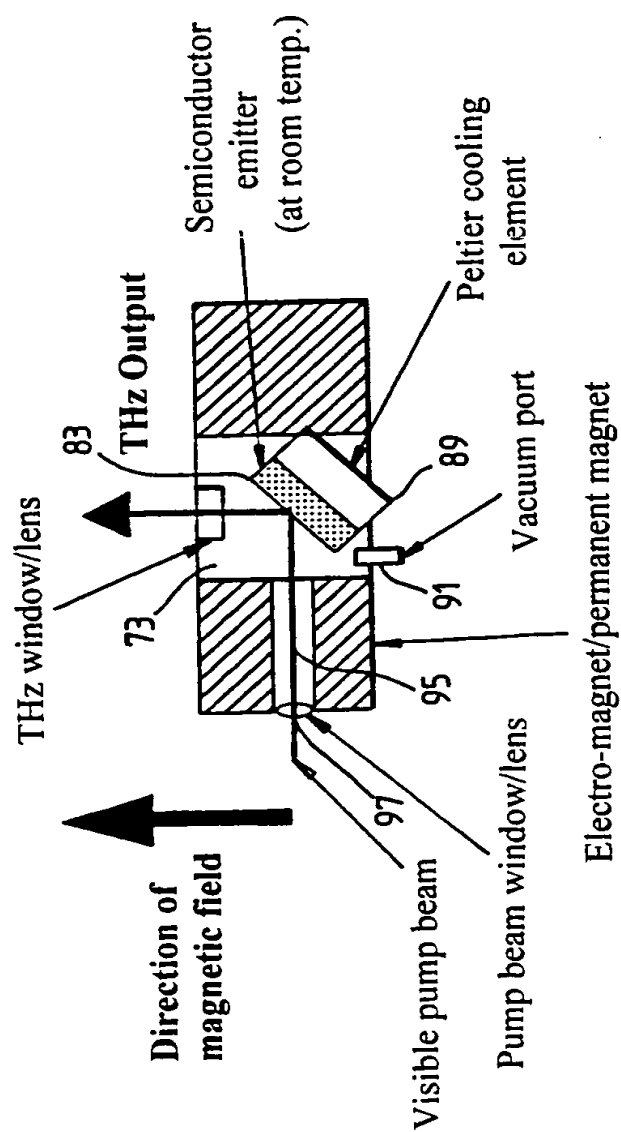


Fig.13

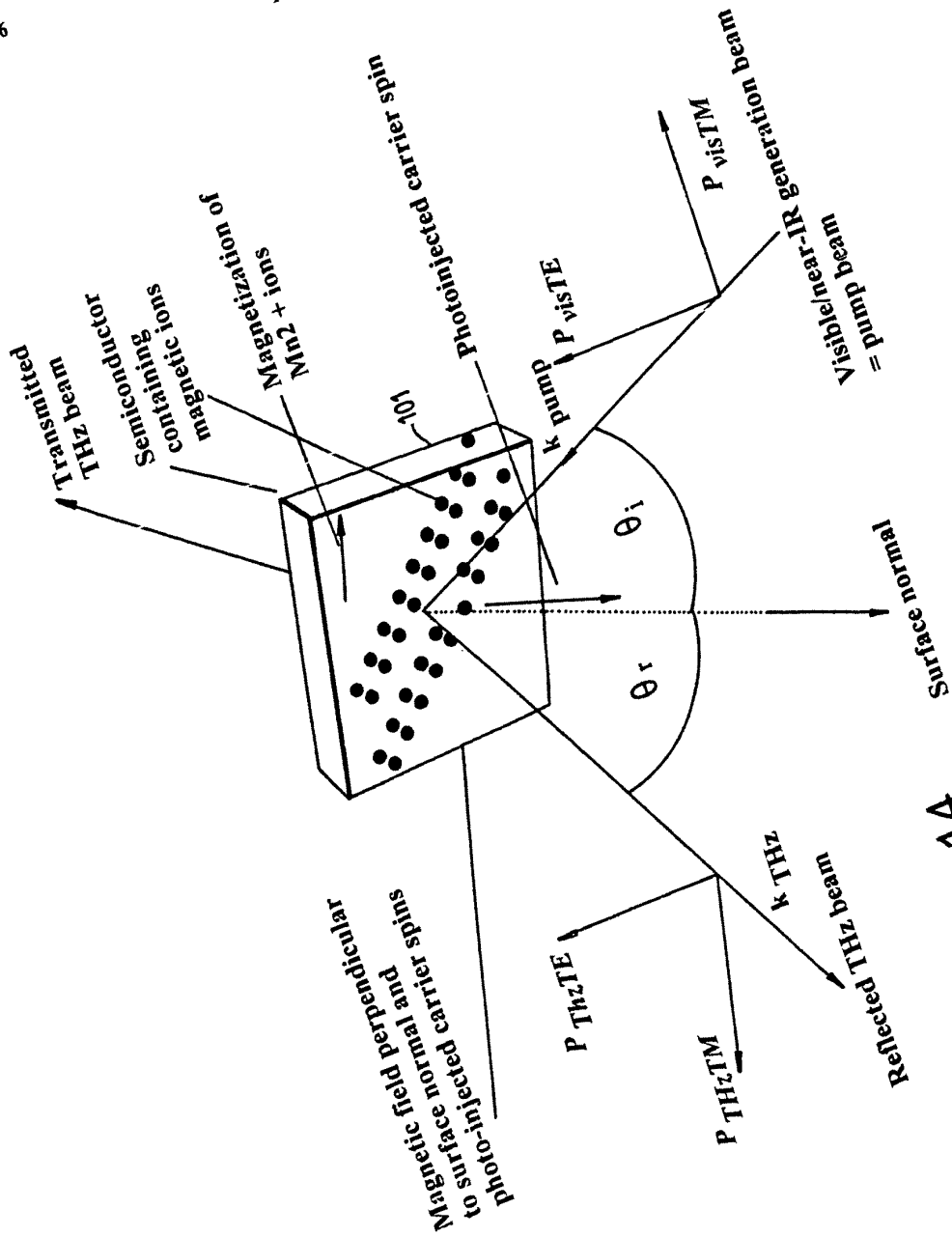


Fig. 14

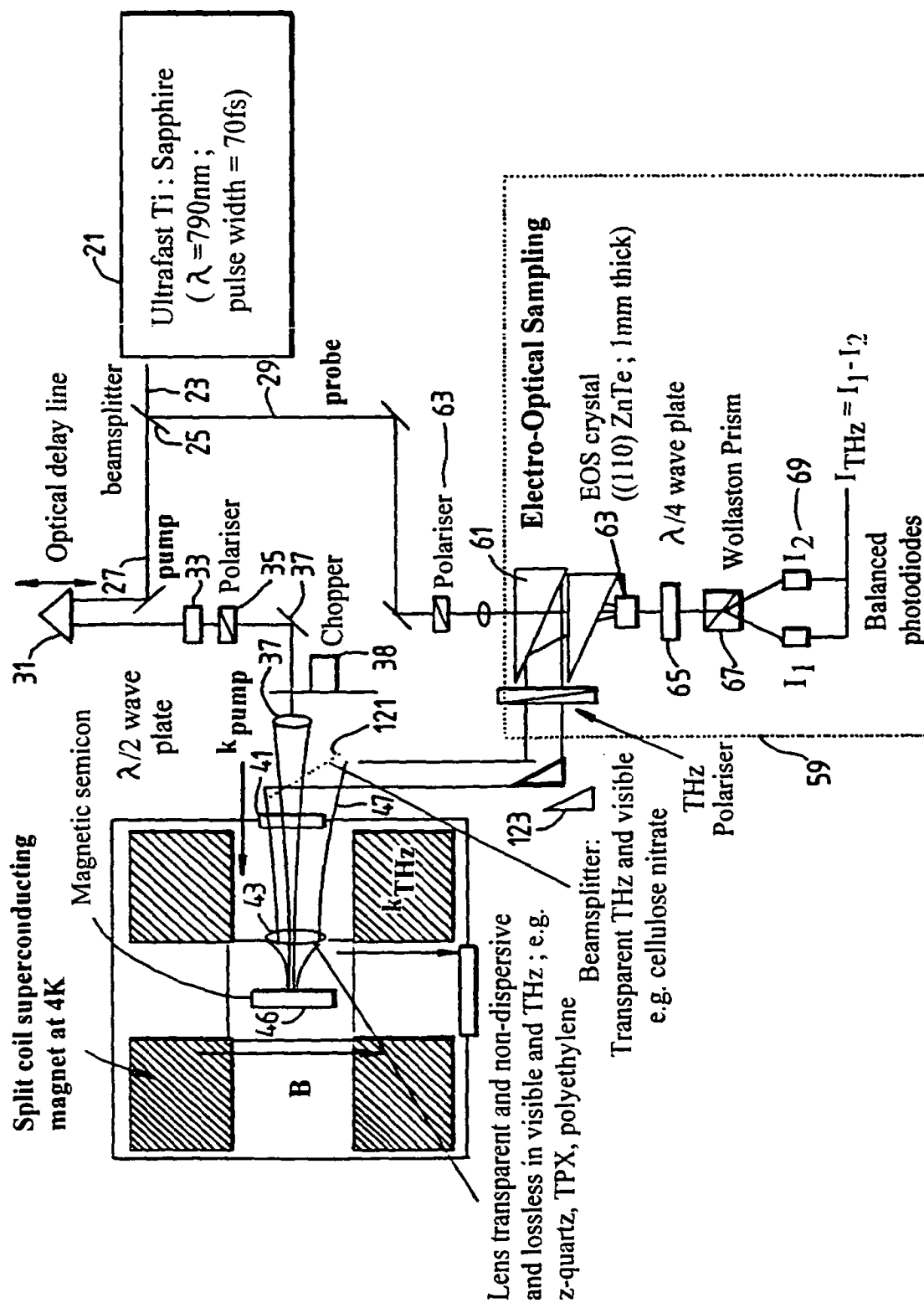


Fig. 15

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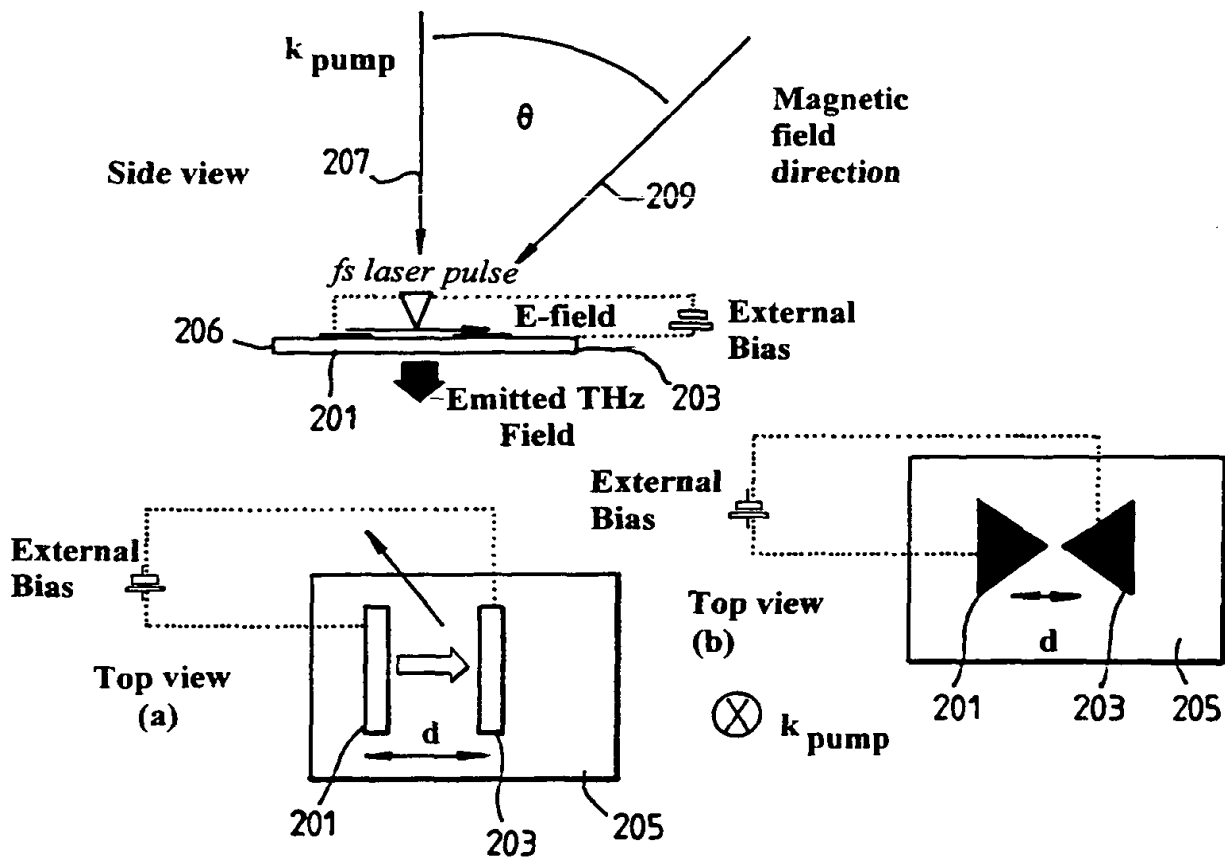


Fig.16

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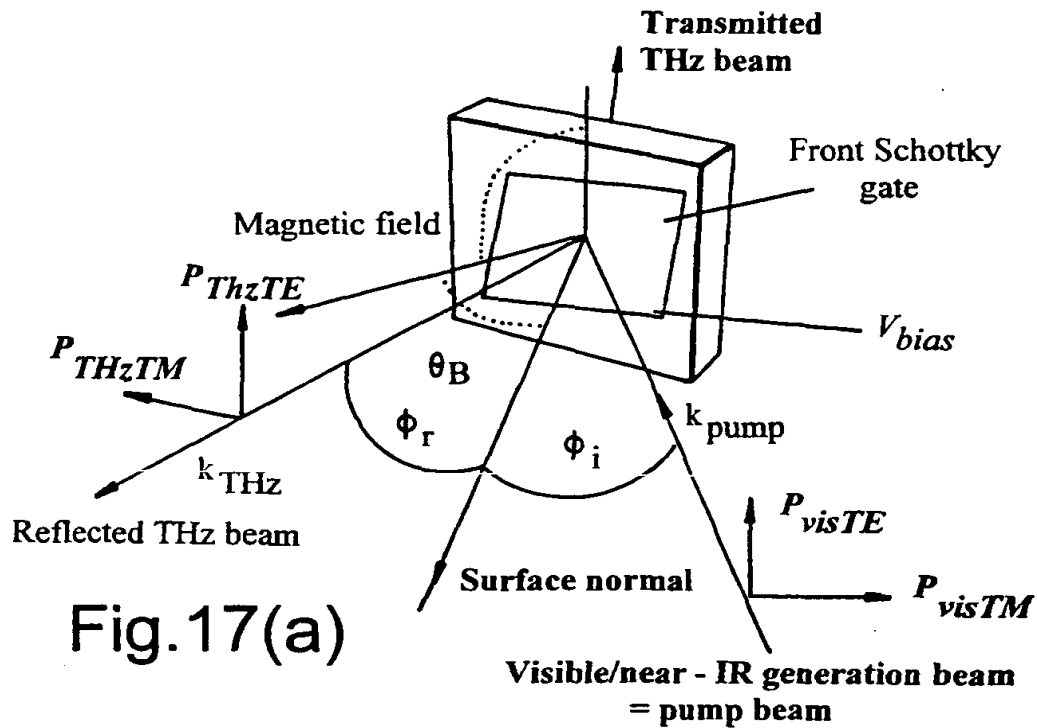


Fig.17(a)

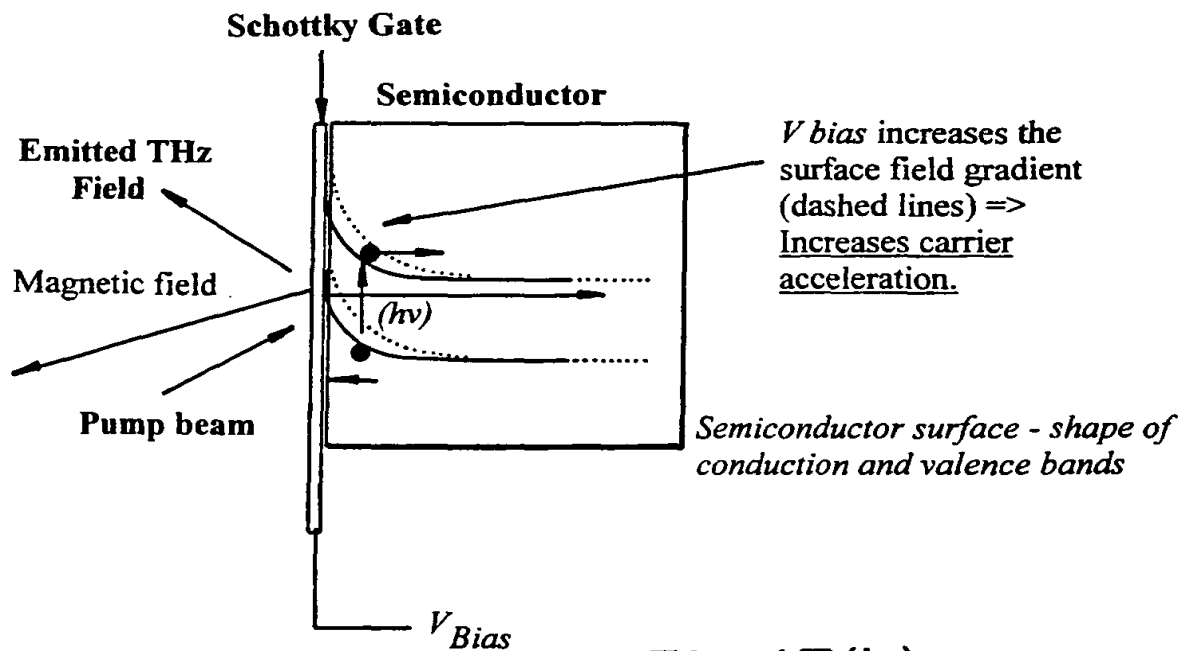


Fig.17(b)

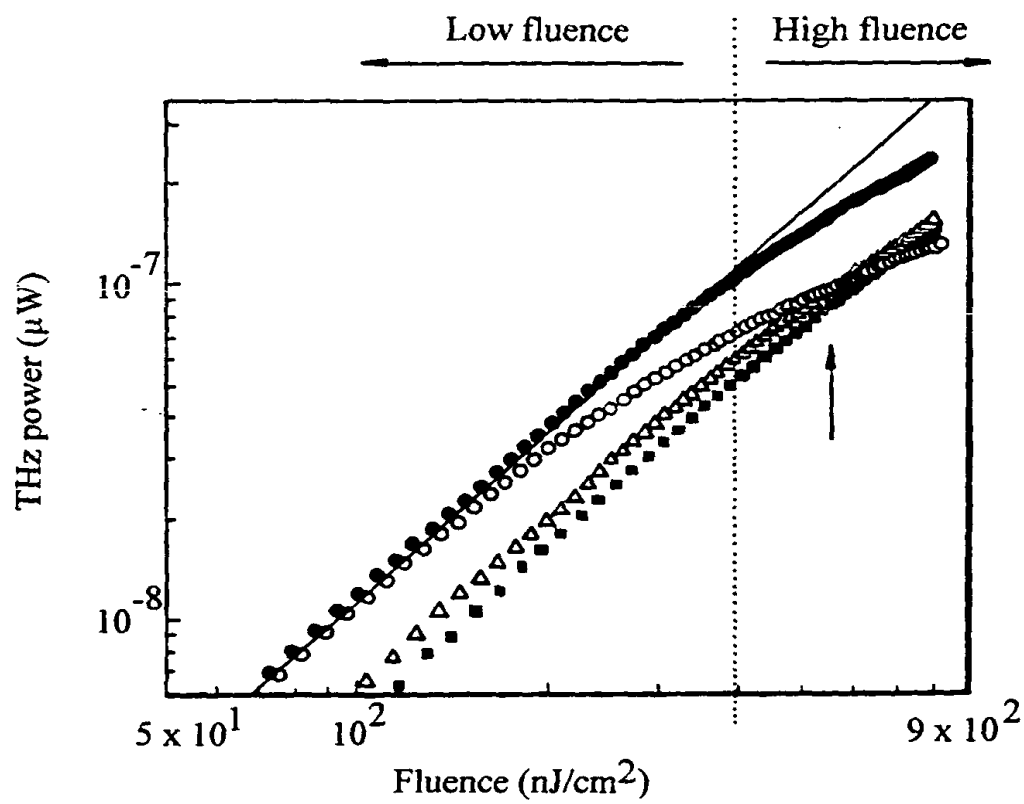


Fig. 18

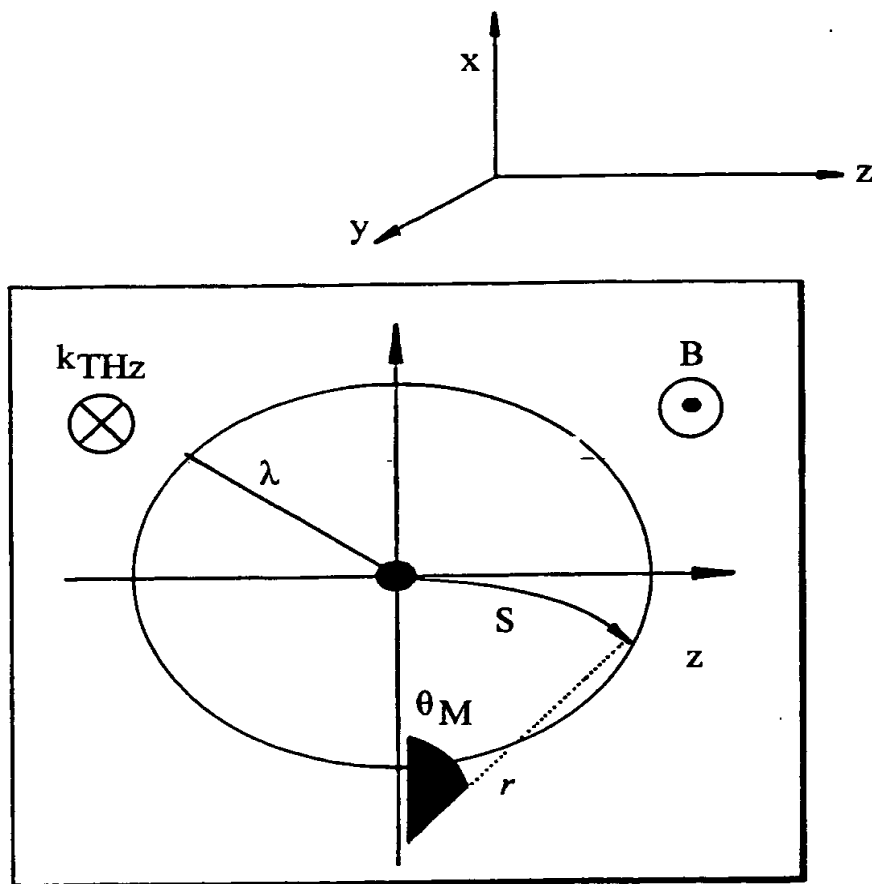


Fig. 19

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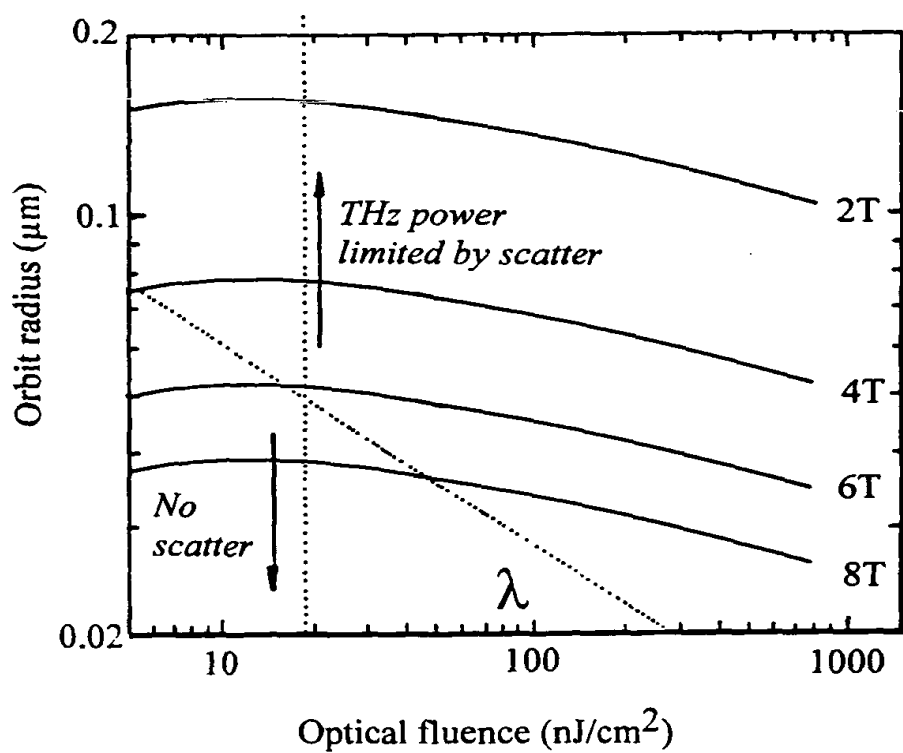


Fig. 20

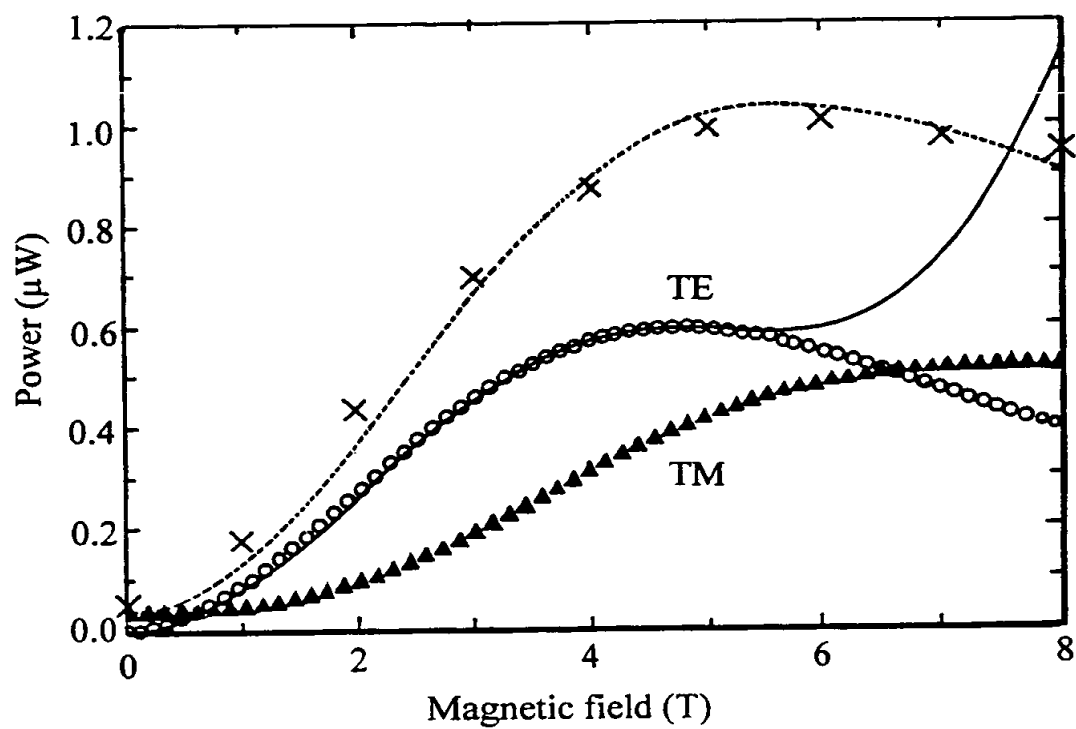


Fig. 21

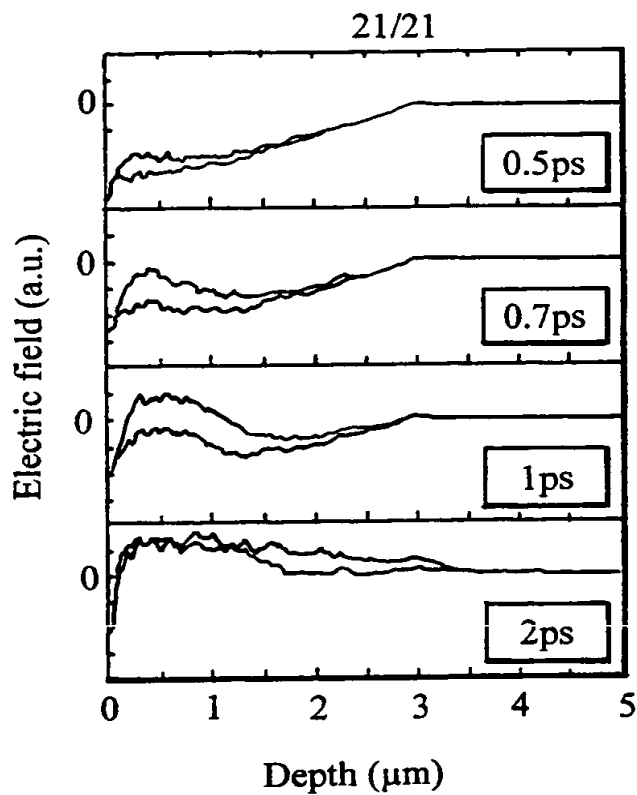


Fig. 22

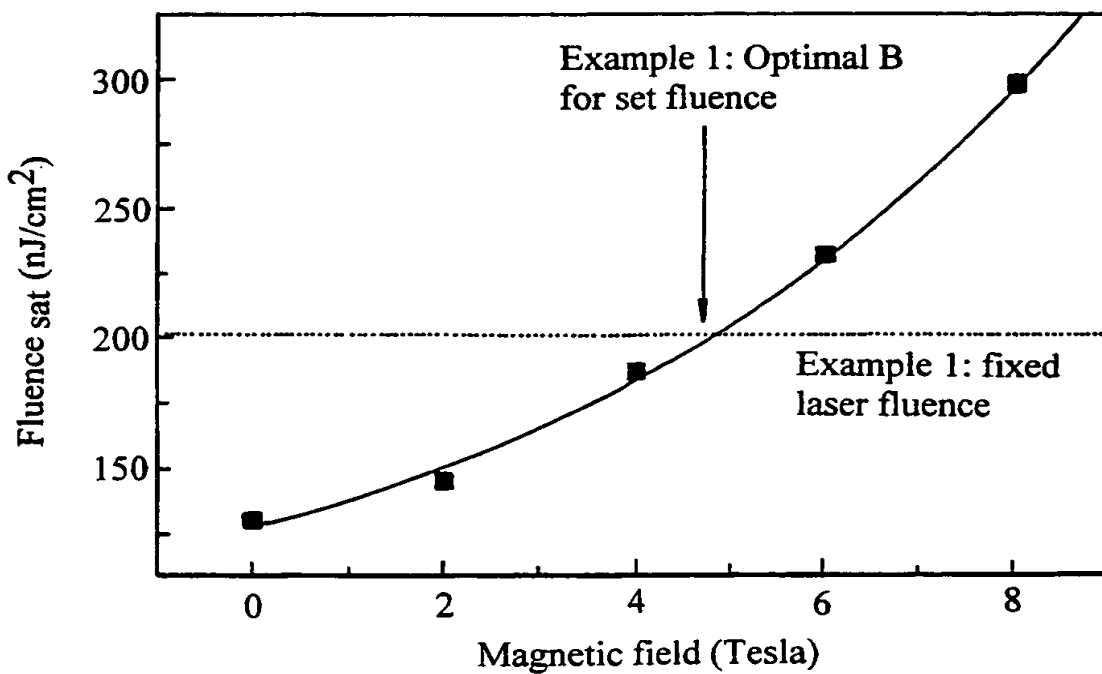


Fig. 23